Addressing outstanding uncertainties associated with high clouds

Sylvia Sullivan, University of Arizona

Thabo Makgoale, University of Arizona
Edgardo Sepúlveda Araya, University of Arizona
Aiko Voigt, University of Vienna
Annette Miltenberger, University of Mainz
Martina Krämer and Christian Rolf, Forschungszentrum Jülich
Athanasios Nenes, Ecole Polytechnique Fédérale de Lausanne
Dongmin Lee, Goddard Space Flight Center
Lazaros Oreopoulos, Goddard Space Flight Center
Corinna Hoose, Alexei Kiselev and Thomas Leisner, Karlsruhe Institute of Technology

Micro2Macro workshop
October 28, 2024

Image from www.visibleearth.nasa.gov/images/85943/cirrus-clouds-off-the-coast-of-chile

Atmospheric model resolutions are decreasing…

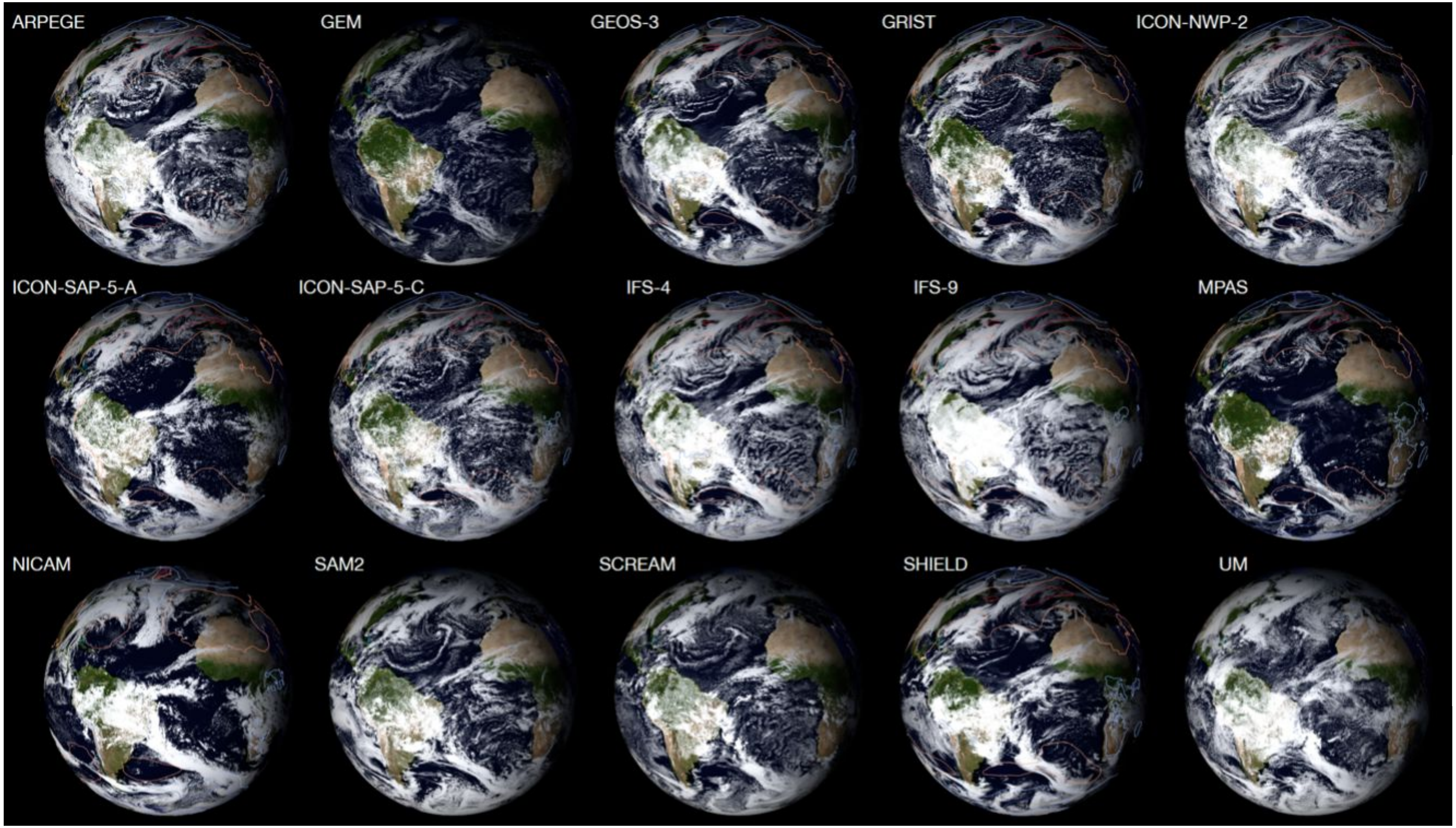
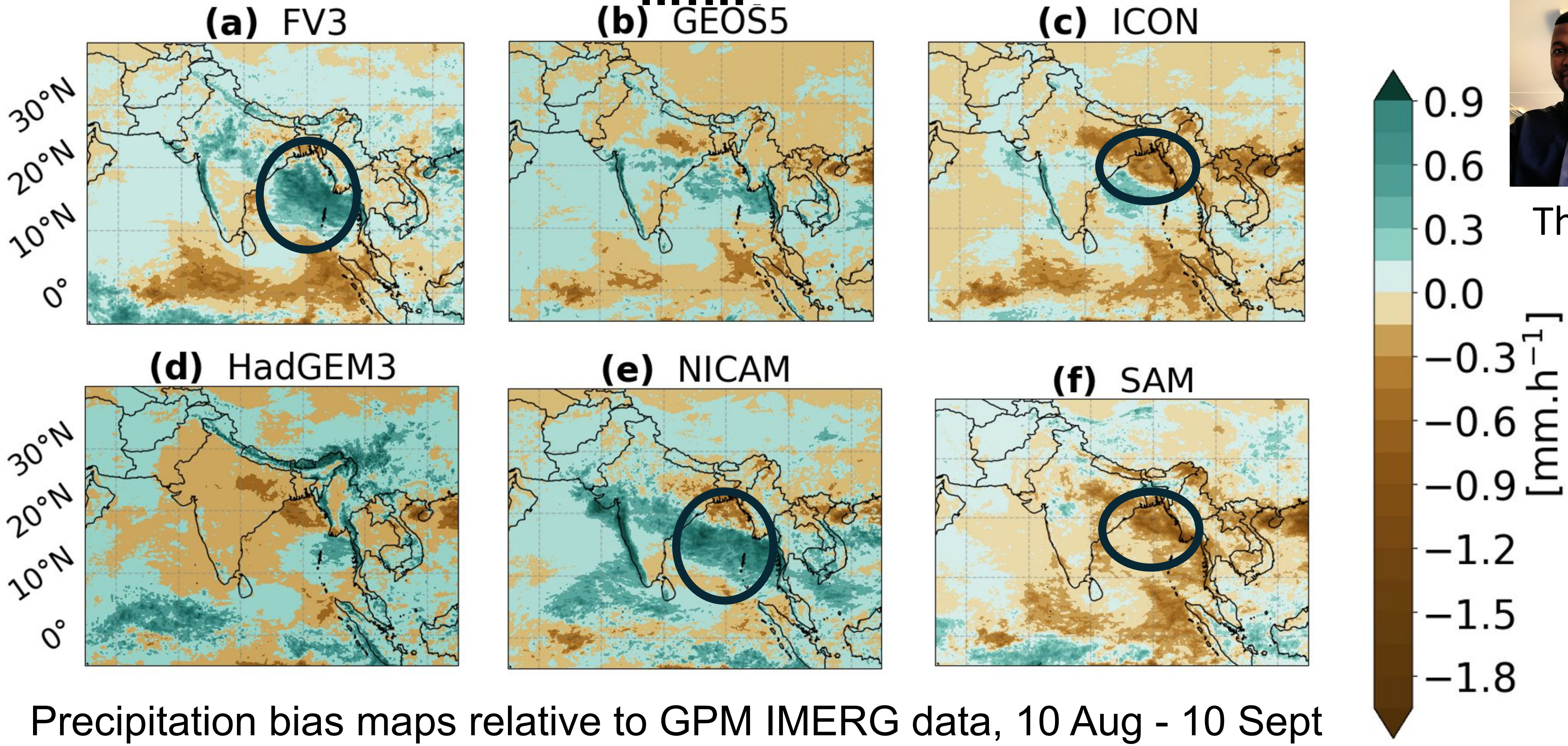


Image from www.gewex.org/dyamond

DYnamics of the **A**tmospheric general circulation **M**odeled **O**n **N**on-hydrostatic **D**omains (DYAMOND) intercomparison

Atmospheric model resolutions are decreasing…

but benefits of this refinement have a limit

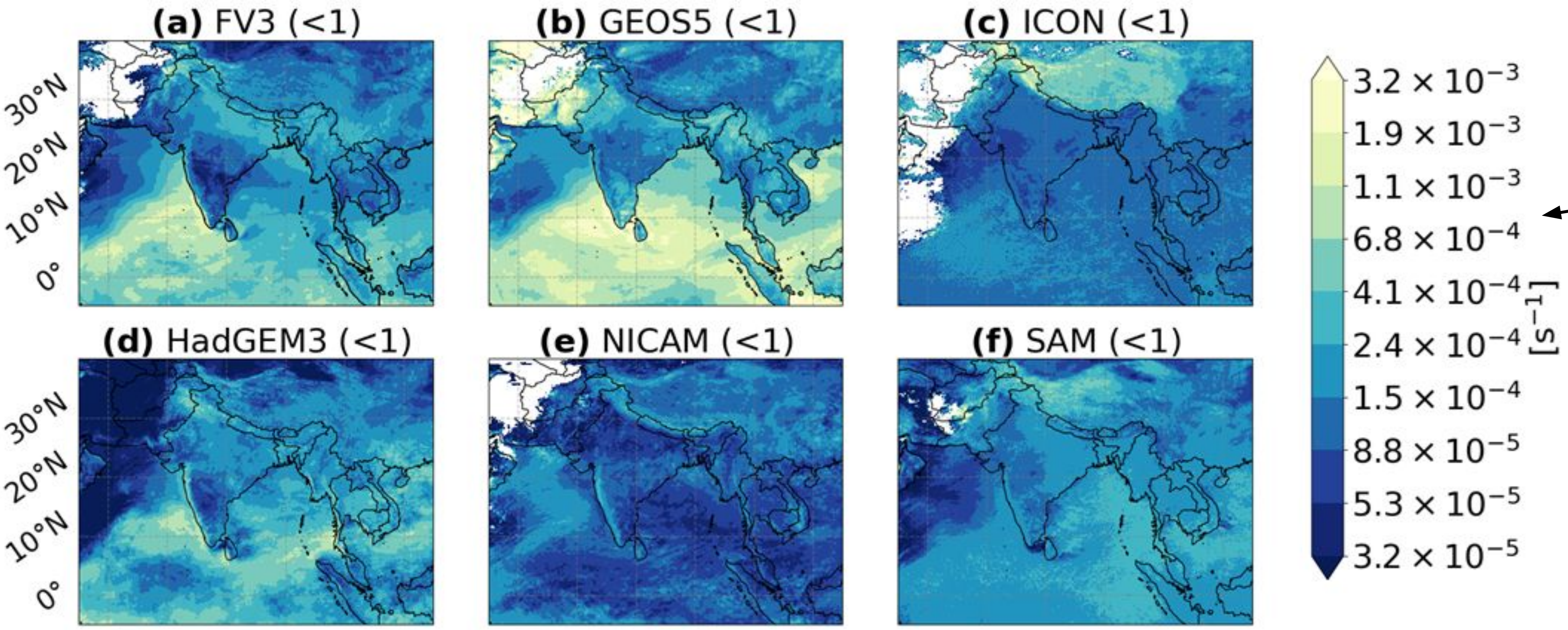


Thabo

Precipitation bias maps relative to GPM IMERG data, 10 Aug - 10 Sept 2017

Makgoale and Sullivan (2024) *under*

Conversion rates of condensate to $\dot{P}$ are very different from one model to the next.



Inverse atmospheric residence times

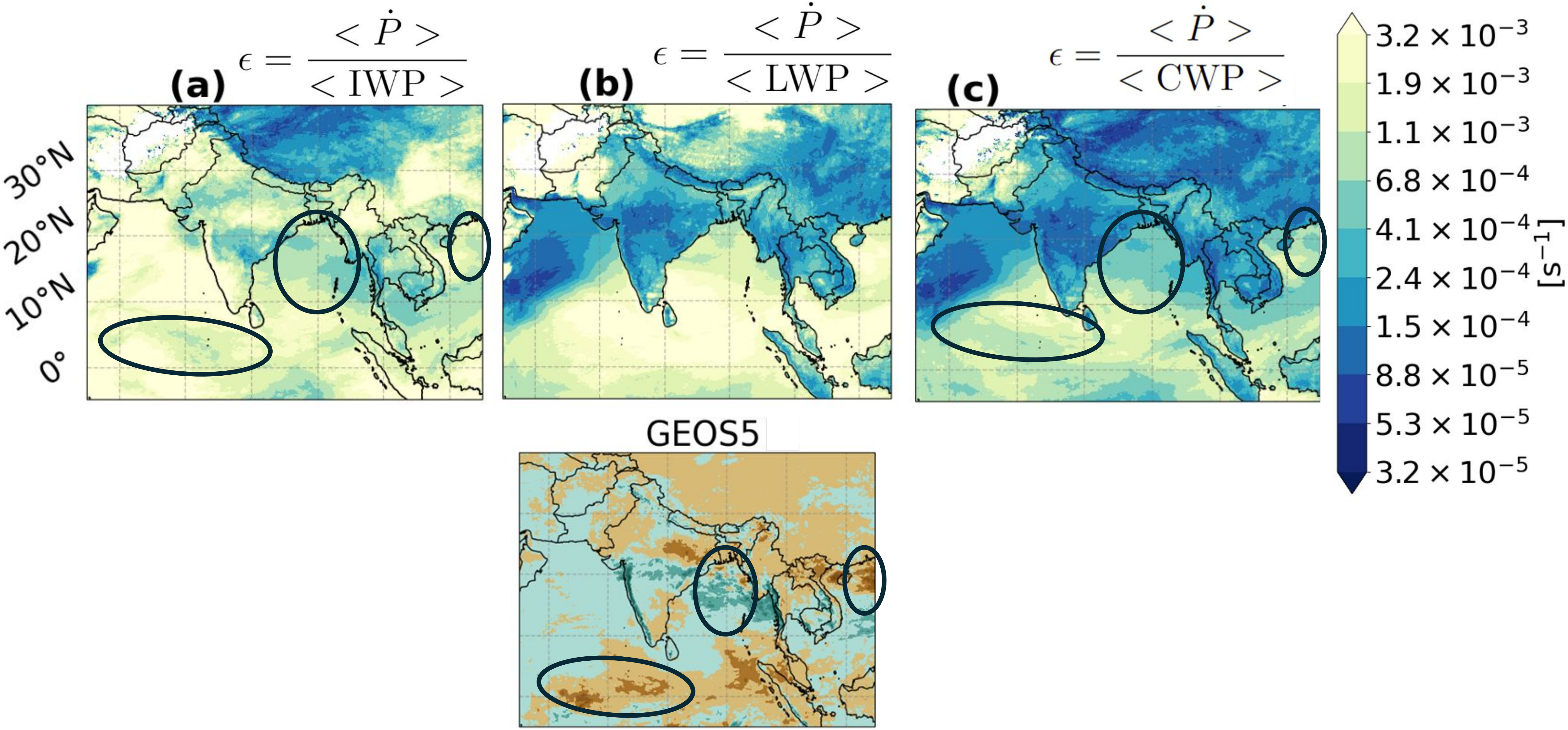
$$\epsilon = \frac{< \dot{P} >}{< \mathrm{CWP} >} \qquad \frac{[\mathrm{kg\ m^{-2}\ s^{-1}}]}{[\mathrm{kg\ m^{-2}}]}$$

rainfall events $\dot{P} < 1$ mm h^{-1}

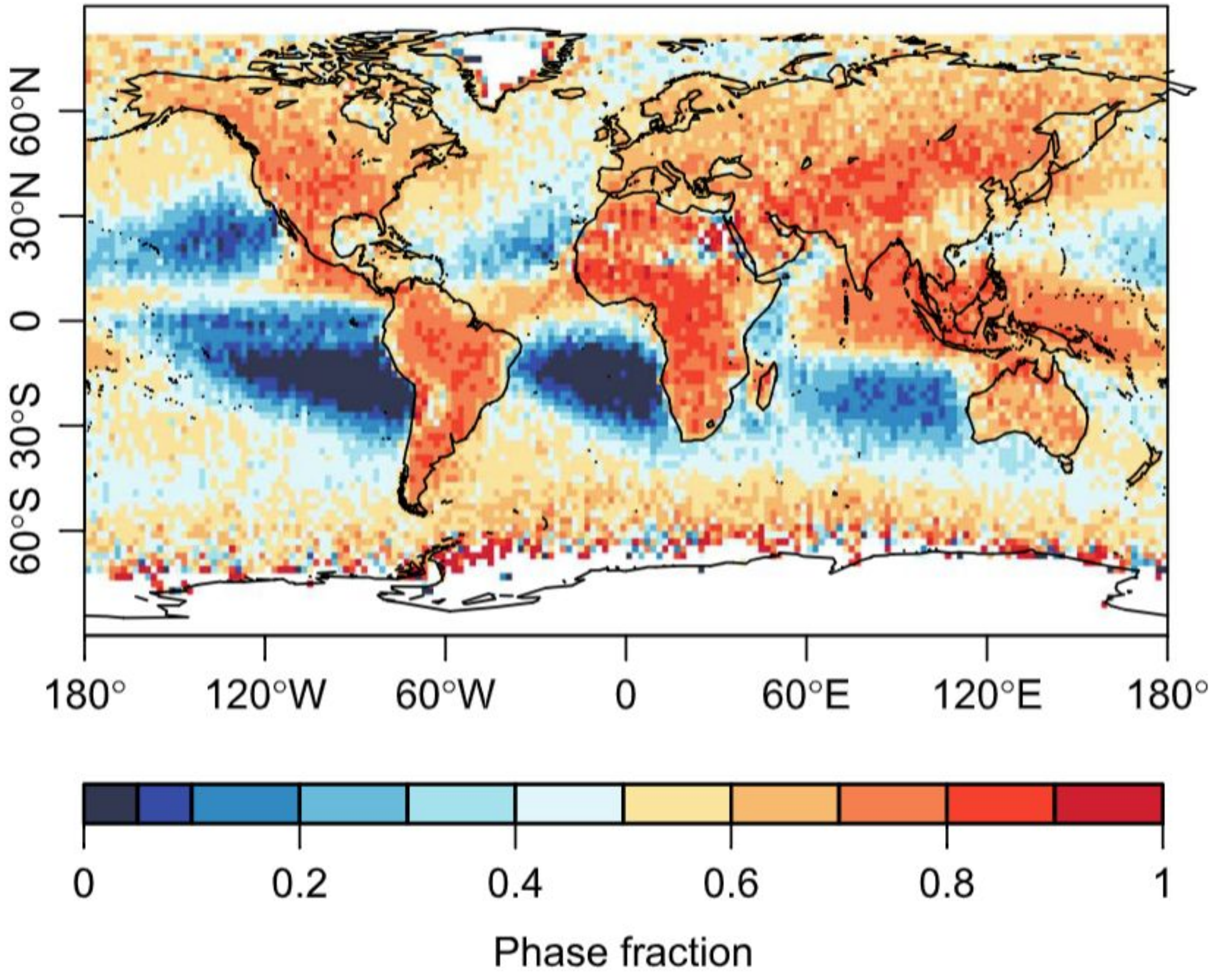
Makgoale and Sullivan (2024) *under*

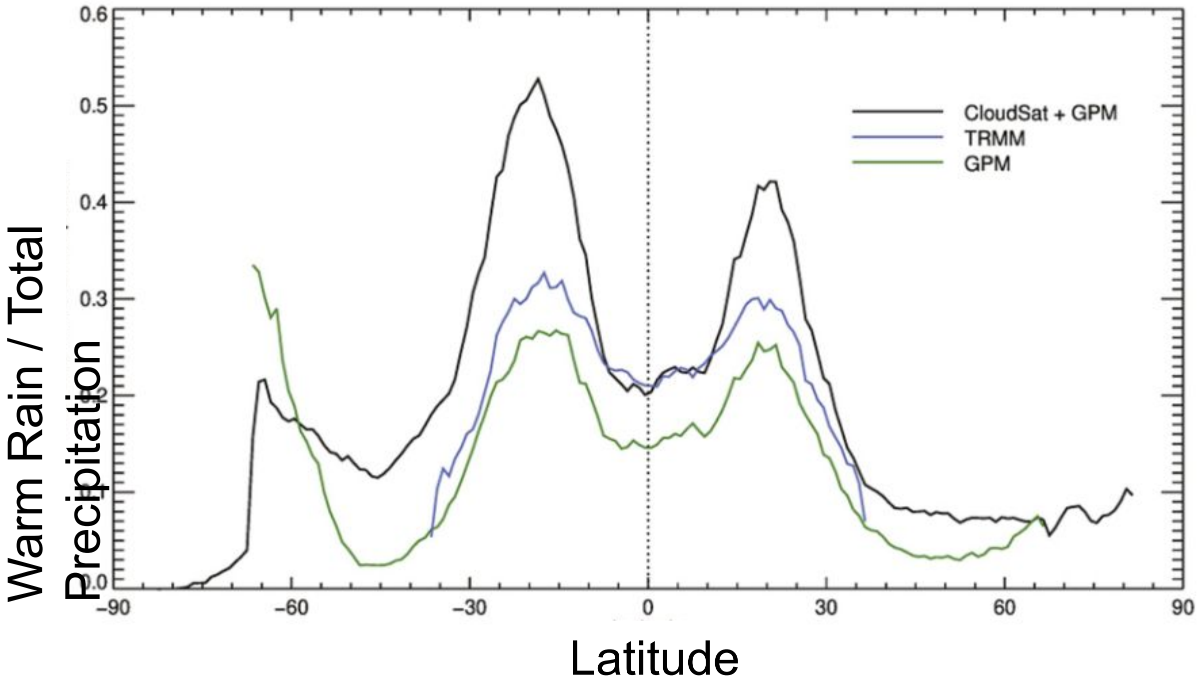
Li et al. 2022 *Nat.*

Where $\dot{P}$ biases are highest, ice water path may play a larger role in setting this conversion rate.



Ice-phase processes play an important role in surface precipitation.



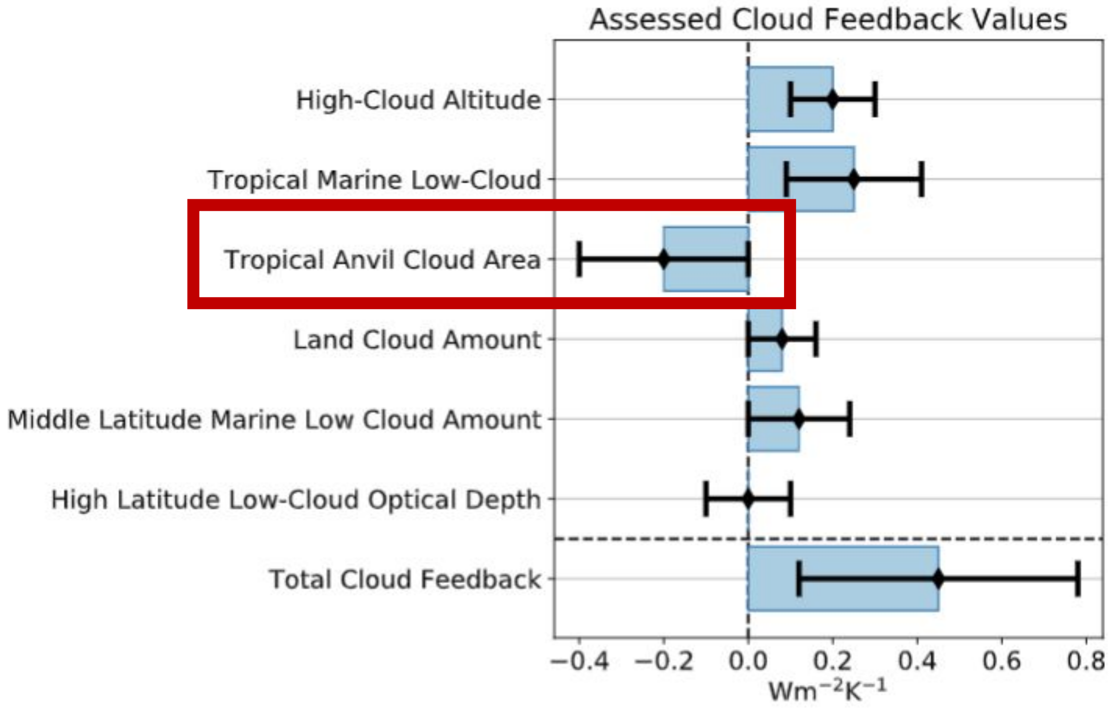


Heymsfield et al. (2020) *J. Atm. Sci.*

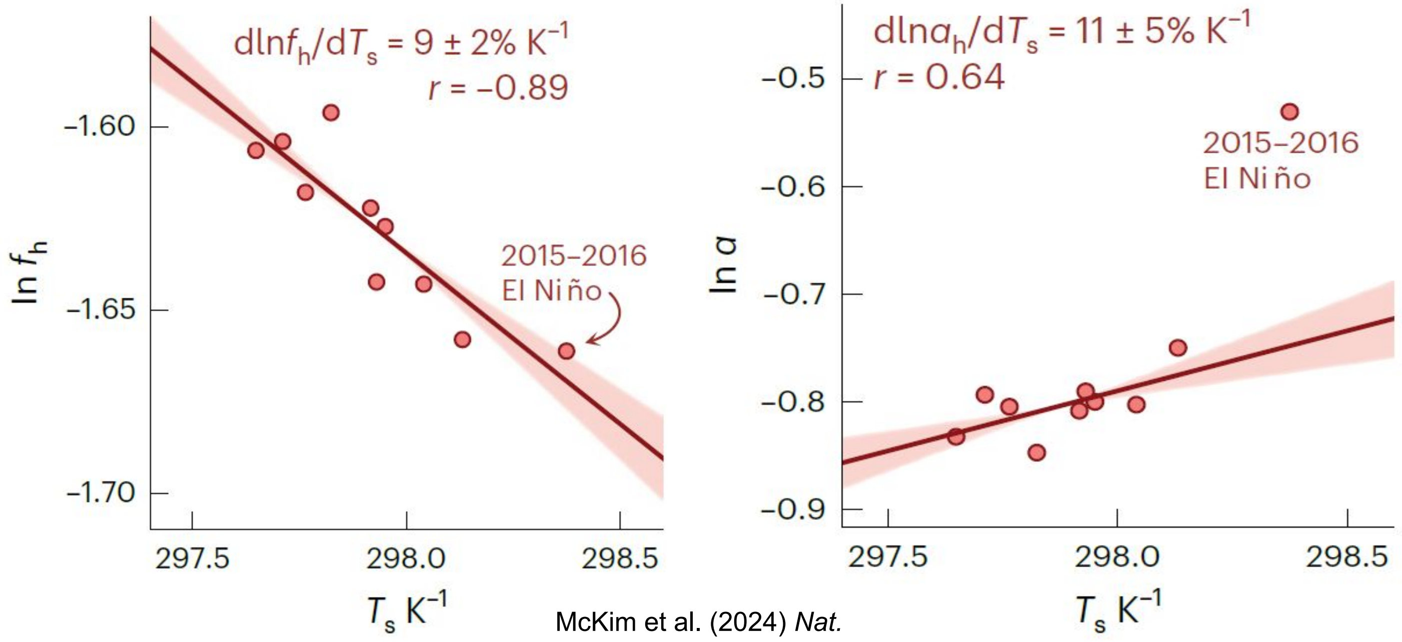
Mülmenstädt et al. (2015) *Geophys. Res. Lett.*

Ice clouds contribute important uncertainties to equilibrium climate sensitivity.

Δ(anvil albedo) with warming has greater uncertainty than the Δ(anvil area)



Sherwood et al. (2020) *Rev. Geophys.*

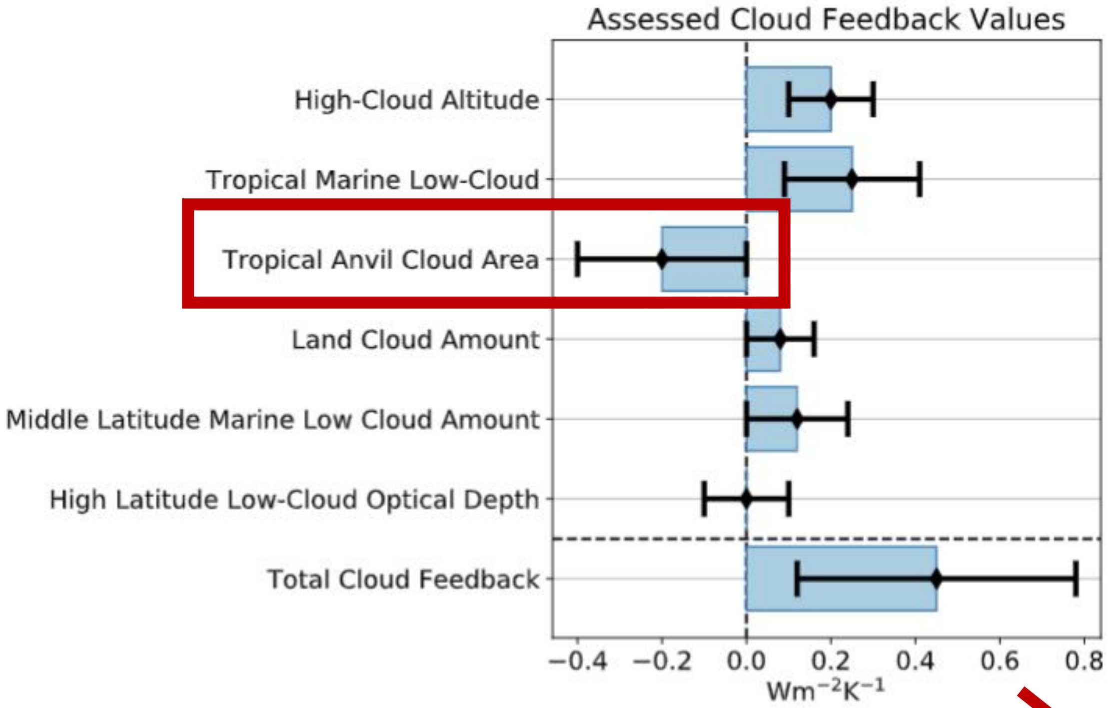


McKim et al. (2024) *Nat. Geosci.*

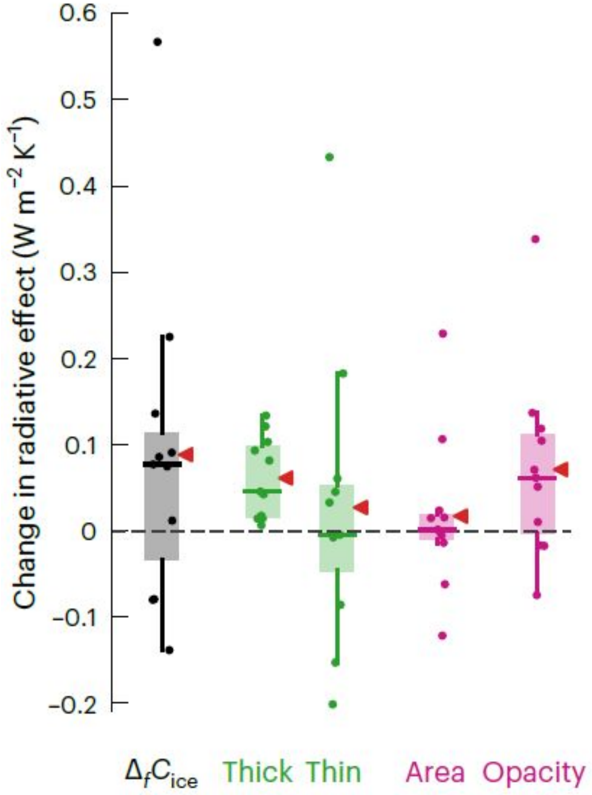
Ice clouds contribute important uncertainties to equilibrium climate sensitivity.

Δ(anvil albedo) with warming has greater uncertainty than the Δ(anvil area)

McKim et al. (2024) *Nat. Geosci.*



Sherwood et al. (2020) *Rev. Geophys.*

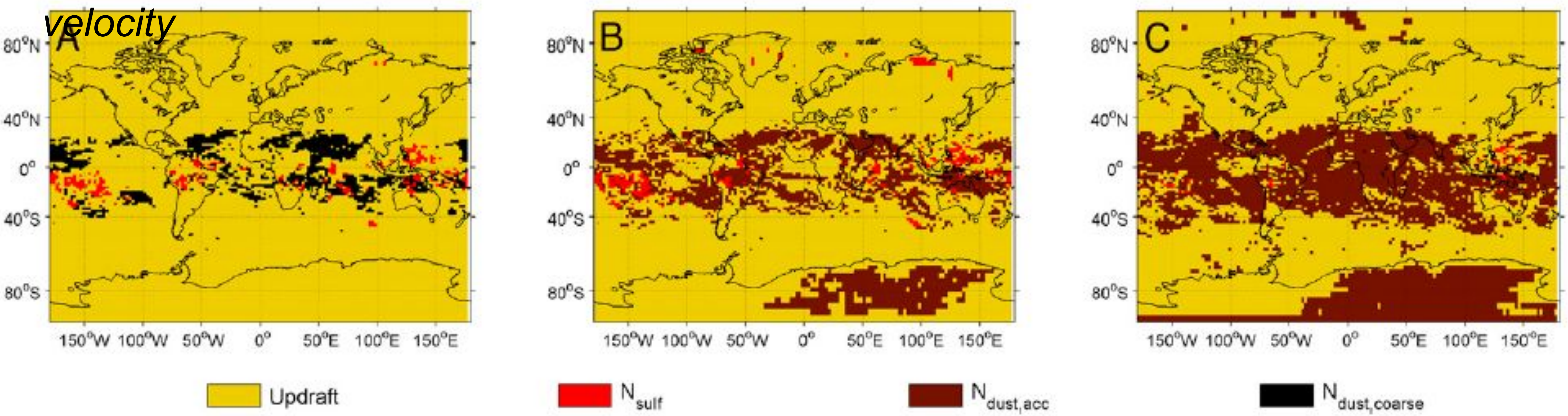


Sokol et al. (2024) *Nat. Geosci.*

Δ(thin ice cloud CRE) with warming have greater uncertainty than the Δ(thick ice cloud

Issue 1: Ice clouds have strong sensitivities to variables for which observations are limited or uncertain.

such as updraft velocity



sensitivity — *input variance*

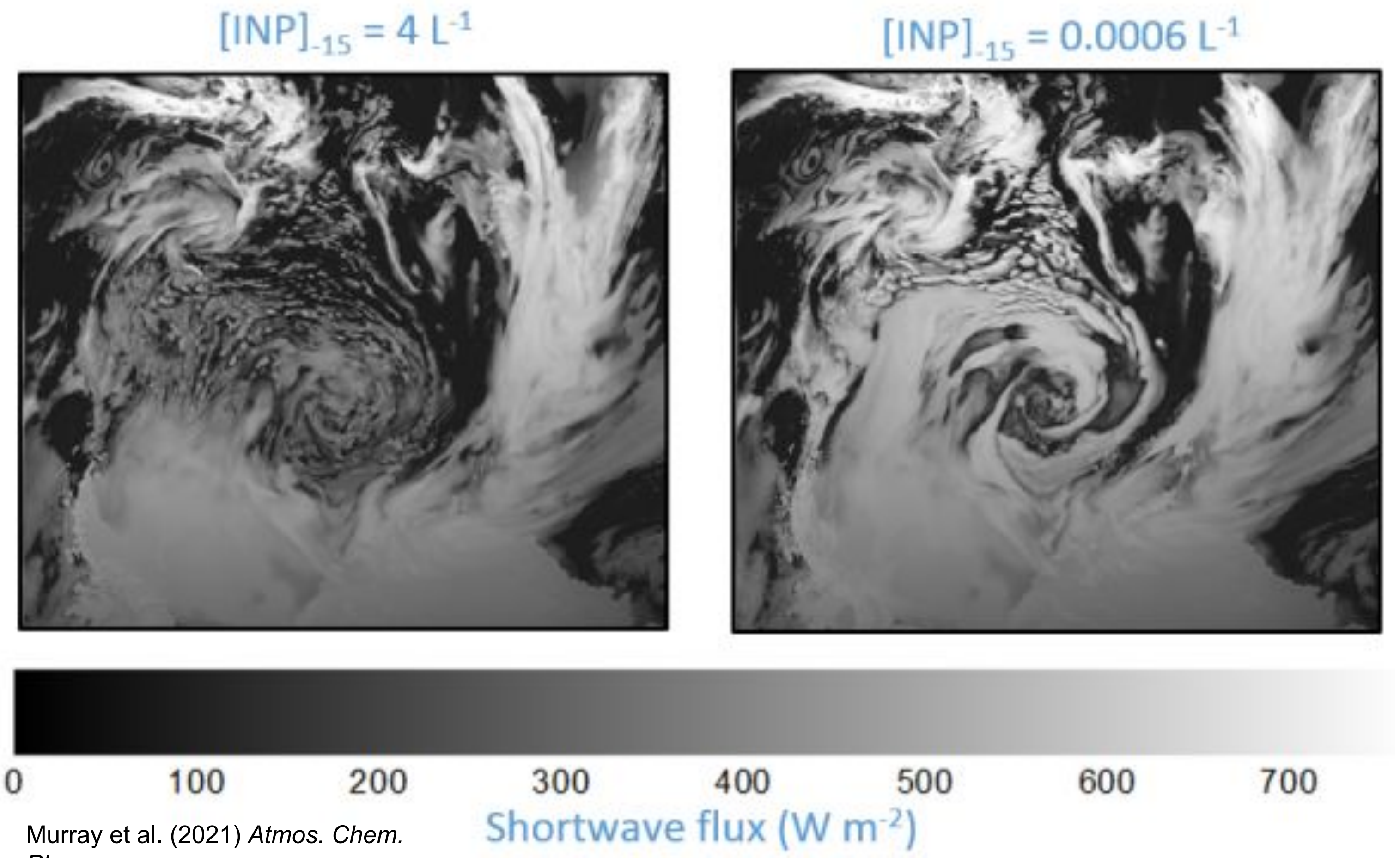
$$\xi_{x_j}^{(N_i)} = \frac{\overline{(\partial N_i/\partial x_j)}^2 \sigma_{x_j}^2}{\sum_{j=1}^{J} \overline{(\partial N_i/\partial x_j)}^2 \sigma_{x_j}^2}$$

Sullivan et al. (2016) *Proc. Nat. Acad. Sci.*

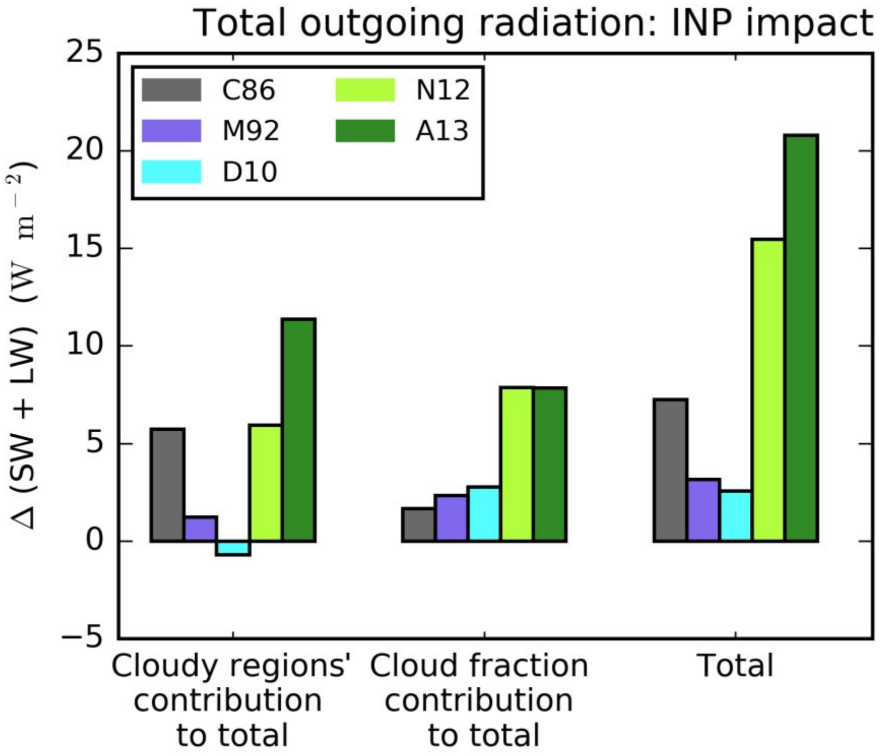
Other studies with similar findings: Donner et al. (2016) *Atmos. Chem. Phys.*, Bühl et al. (2019) *npj Clim. Atm. Sci.*, Bolot et al. (2023) *npj Clim. Atm. Sci.*

Issue 1: Ice clouds have strong sensitivities to variables for which observations are limited or uncertain.

such as ice-nucleating particle concentrations



Murray et al. (2021) *Atmos. Chem. Phys.*



Hawker et al. (2021) *Atmos. Chem. Phys.*

Issue 1b: *But also* ice clouds have strong sensitivities to the structural formulation of microphysics.

We can see this with forms of microphysical piggybacking.

Ice crystals radiatively heat by absorption.

(1)

$$(q_i, N_i) = \phi, \psi(P, T, \omega, u, v)$$

(2)

$$RH \propto (N_i, \int q_i \, \mathrm{d}p')$$

Radiative heating generates buoyant ascent...

$$\frac{\partial \omega}{\partial t} \propto CRH$$

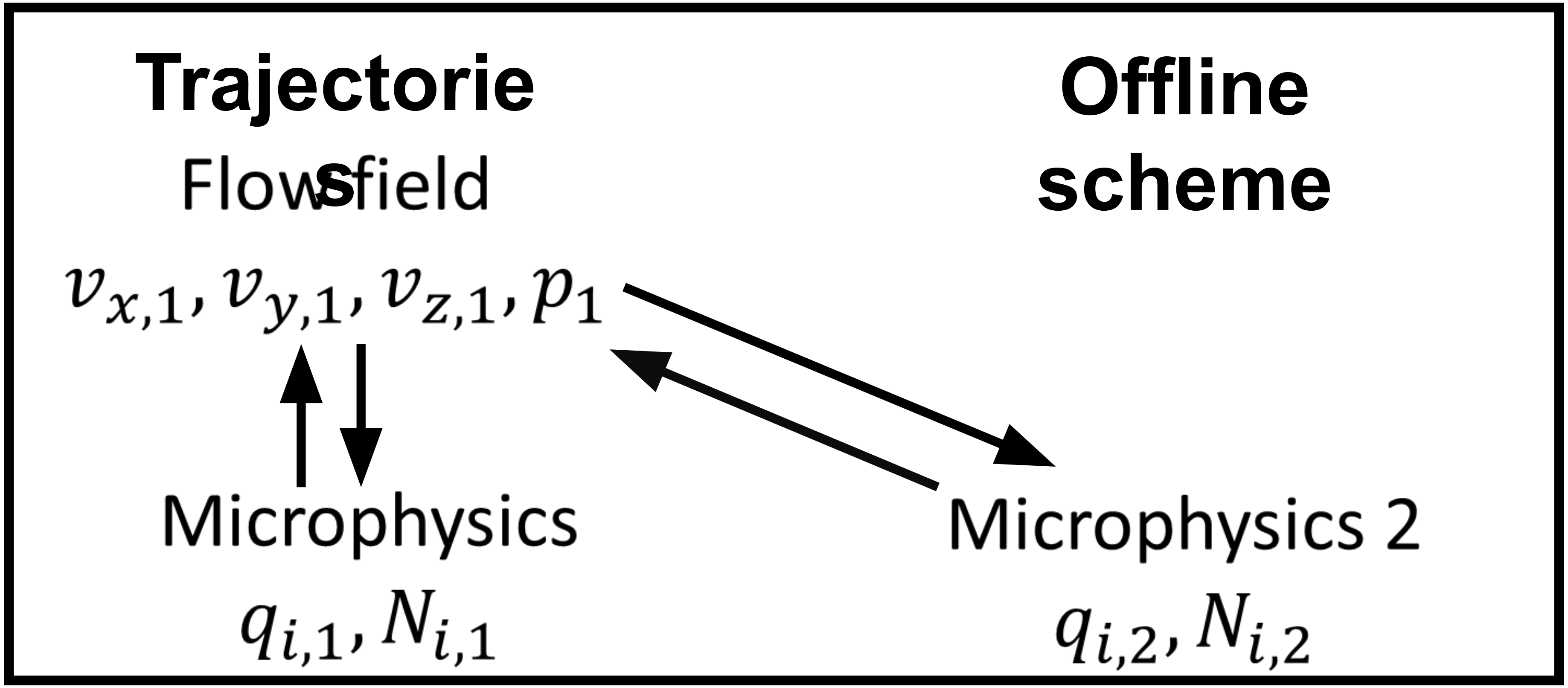
… and ascent produces supersaturation.

Sullivan et al. (2022) *J. Adv. Model Earth Sys.*

Issue 1b: *But also,* ice clouds have strong sensitivities to the structural formulation of microphysics.

We can see this with forms of microphysical piggybacking.

"Lagrangian piggybacking"



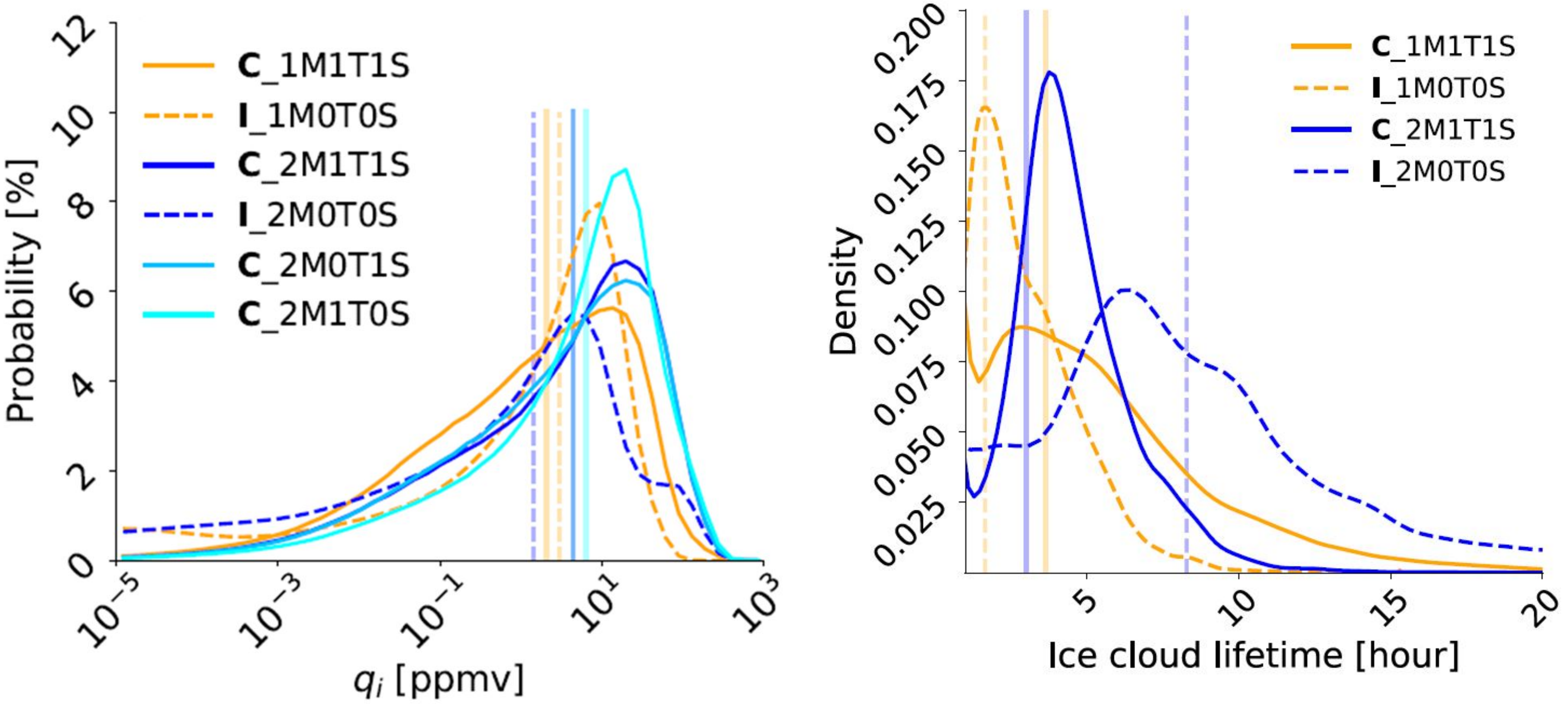
1- or 2-moment schemes in ICON

2-moment scheme in CLaMS-Ice

JÜLICH Forschungszentrum

Sullivan et al. (2022) *J. Adv. Model Earth Sys.*

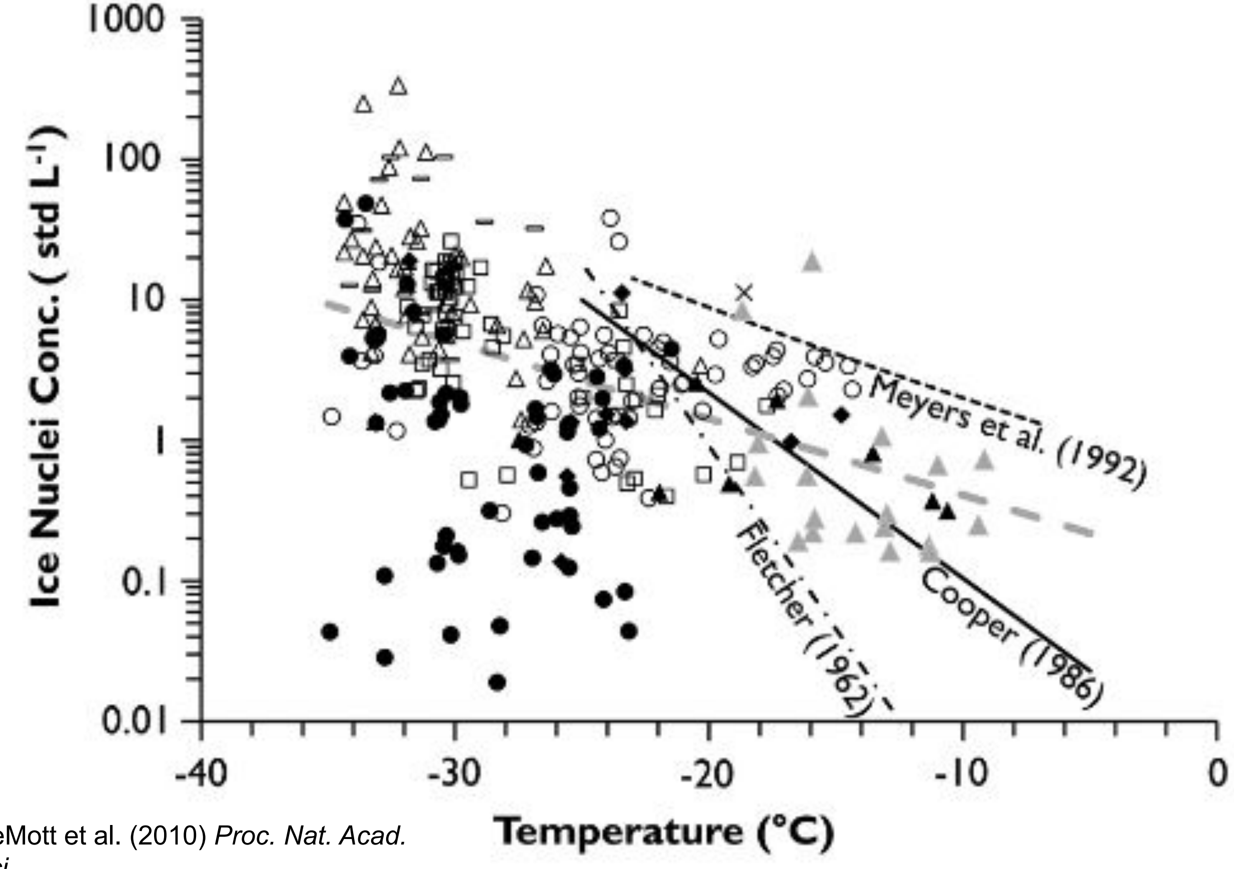
Issue 1b: *But also,* ice clouds have strong sensitivities to the structural formulation of microphysics.



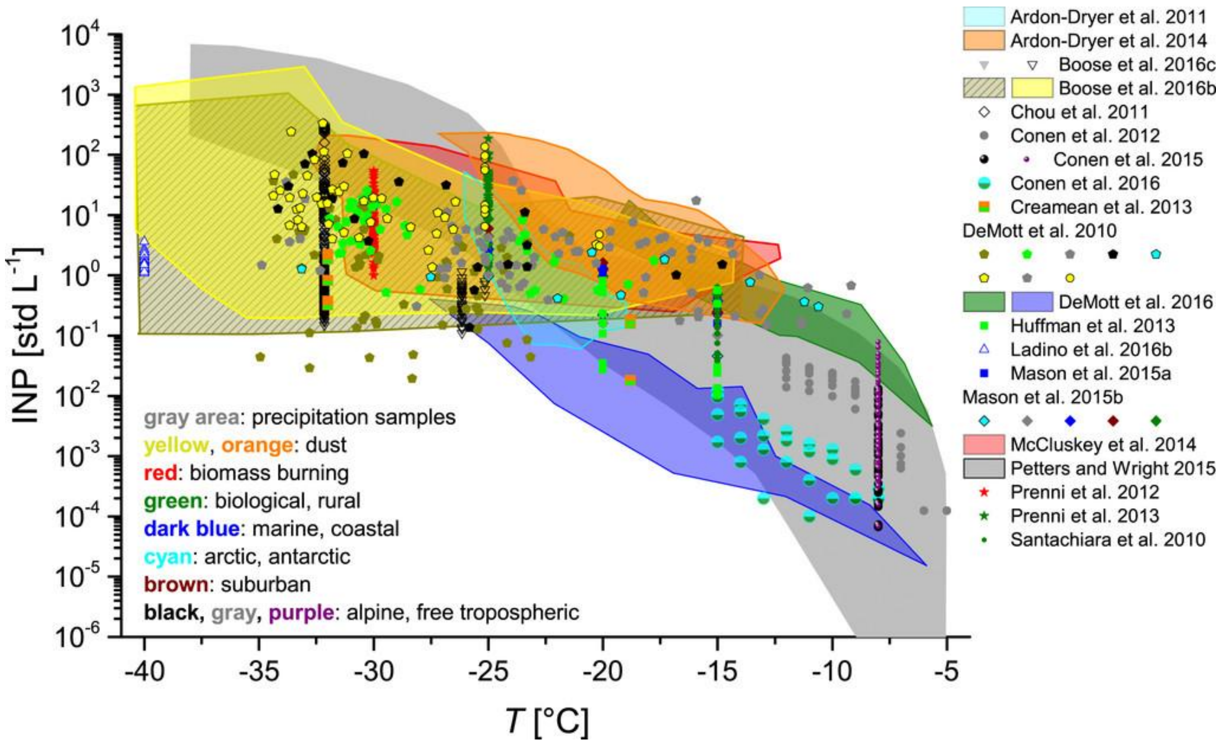
Sullivan et al. (2022) *J. Adv. Model Earth Sys.*

Issue 2: It is unclear how many (and which) degrees of freedom are needed to reliably represent ice microphysical processes.

temperature-dependent-only INP parameterizations are likely insufficient



DeMott et al. (2010) *Proc. Nat. Acad. Sci.*



Kanji et al. (2017)

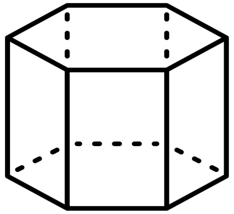
Issue 2: It is unclear how many (and which) degrees of freedom are needed to reliably represent ice microphysical processes.

Should ice optical properties depend on temperature? Ice crystal complexity?

Edgardo

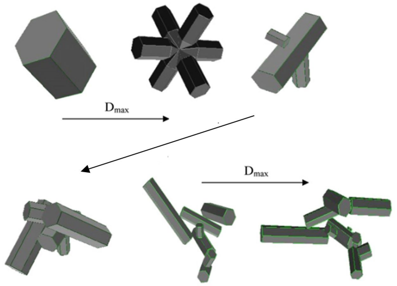
"hierarchy" of optical schemes

(a)



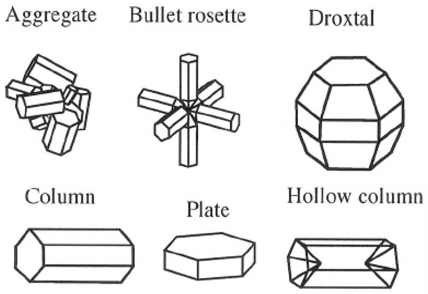
Fu 1996 (SW) and Fu, Yang & Sun 1998 (LW)

(b)



Baran et al. 2016

(c)



Yi et al. 2013

\+ ecRad radiative transfer scheme

idealized ice clouds

`IWP` `r_eff` `T_top`

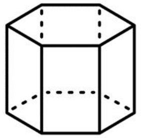
`T_bottom` `T_mid`

`F_LW,up,clr` `F_SW,up,clr`
`F_LW,down,clr` `F_SW,down,clr`
`F_LW,up,cld` `F_SW,up,cld`
`F_LW,down,cld` `F_SW,down,cld`

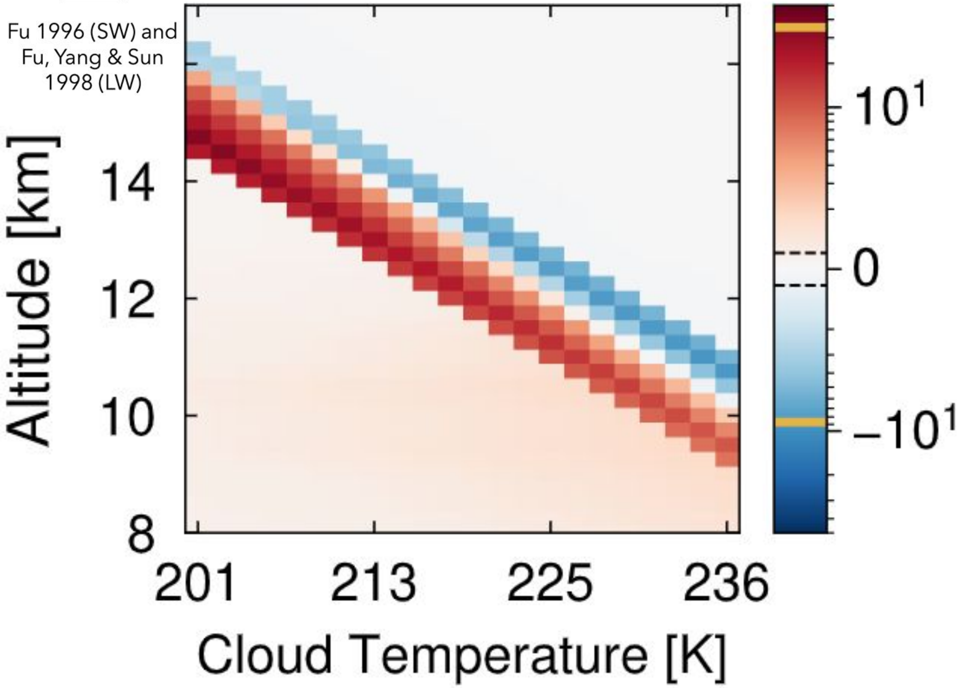
Issue 2: It is unclear how many (and which) degrees of freedom a
needed to reliably represent ice microphysical processes.

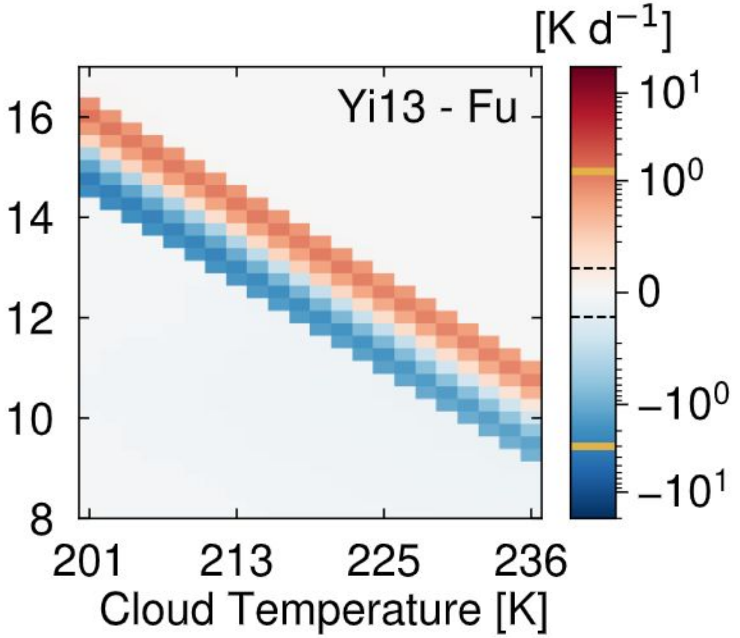
Edgardo

Should ice optical properties depend on temperature? Ice crystal mplexity?



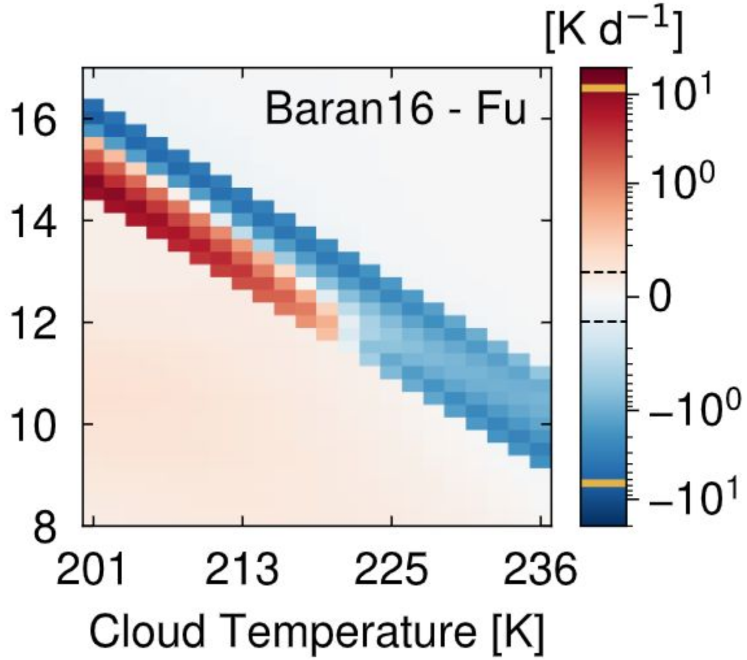
Fu 1996 (SW) and Fu, Yang & Sun 1998 (LW)





including many ice crystal habits and surface roughness →

weakened LW heating



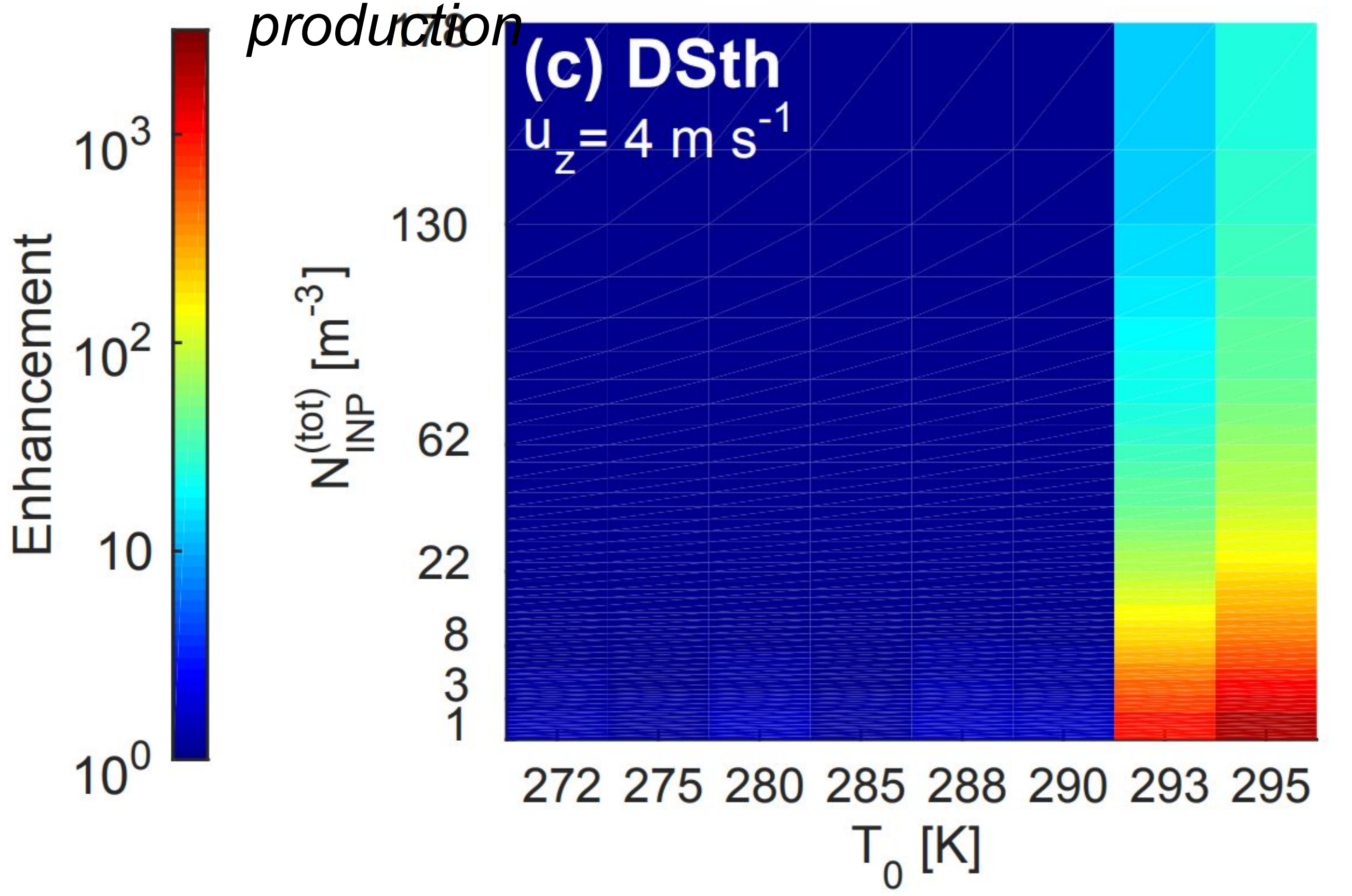
including many ice crystal aggregates and *T* dependence →

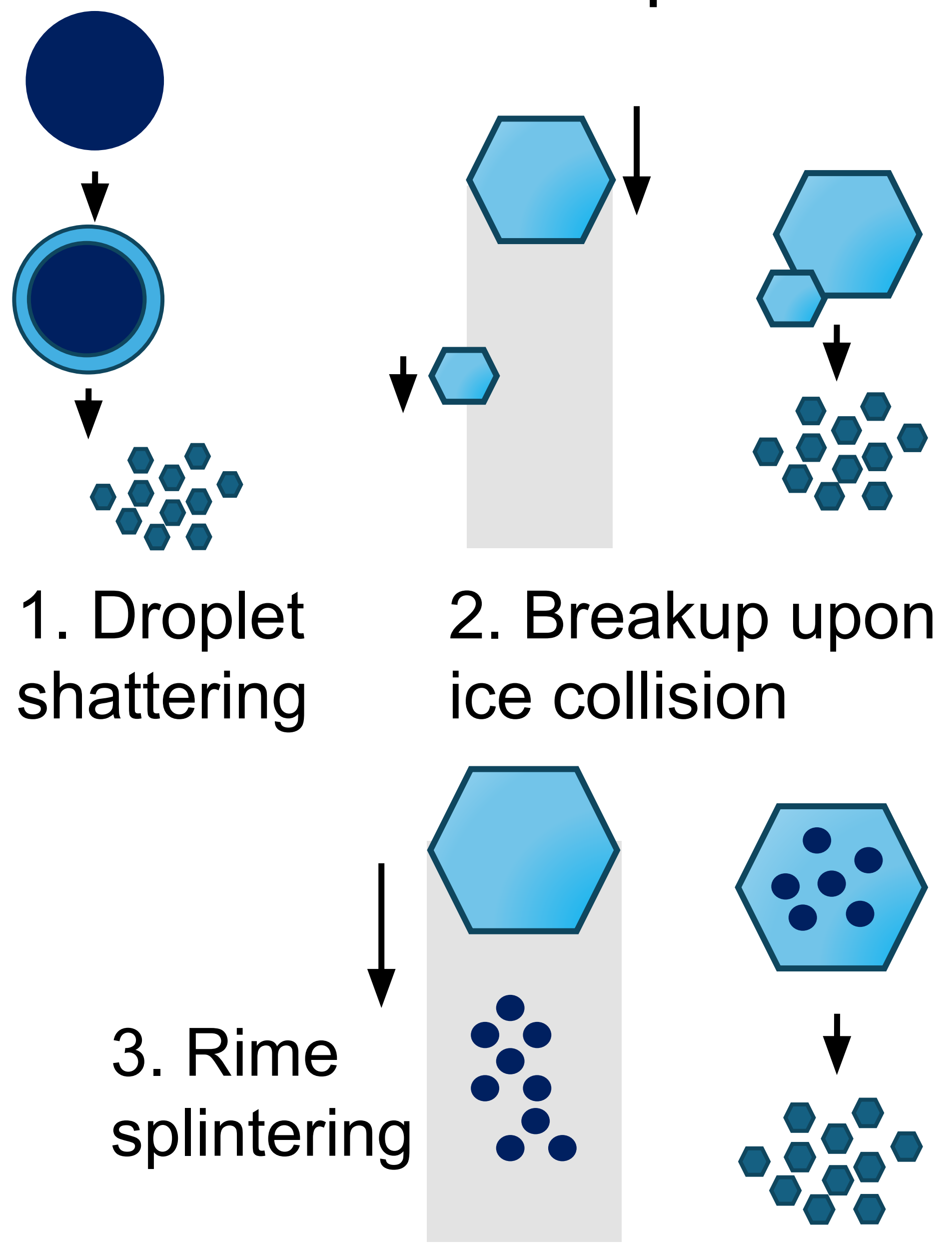
enhanced LW heating

Sepúlveda Araya, Sullivan, and Voigt (2024) *under*

Issue 2b: It is unclear whether all processes need to be represented under all conditions.

such as secondary ice production

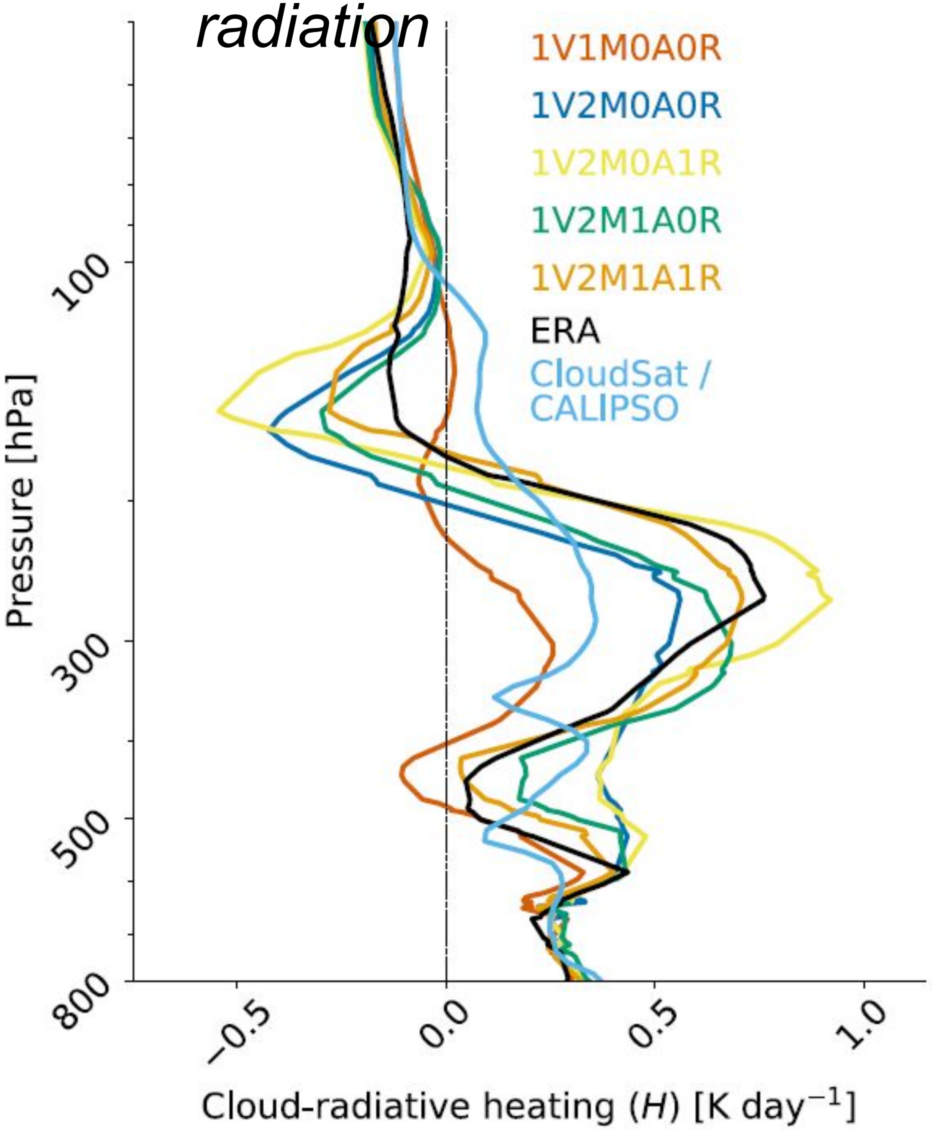




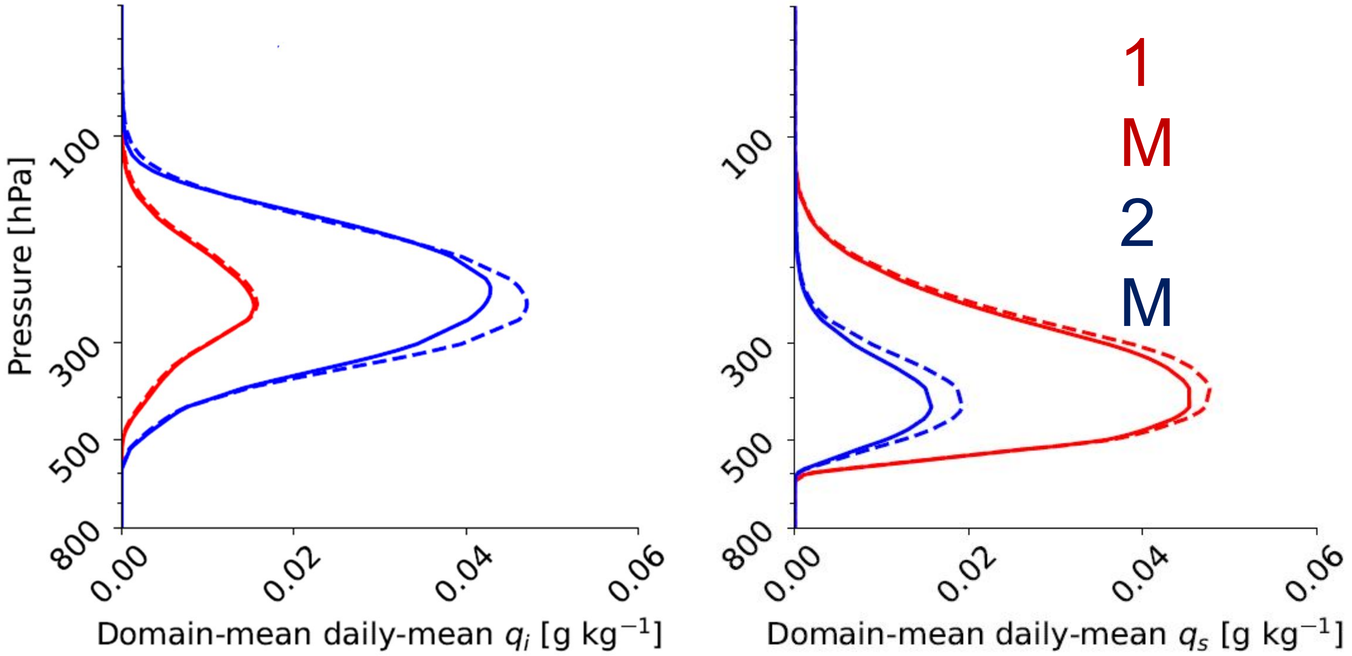
Sullivan et al. (2018) *Atmos. Chem. Phys.*

Issue 3: Certain variables are treated inconsistently across model components

such as ice crystal effective radius between microphysics and radiation



such as snow between microphysics and radiation



1M

2M

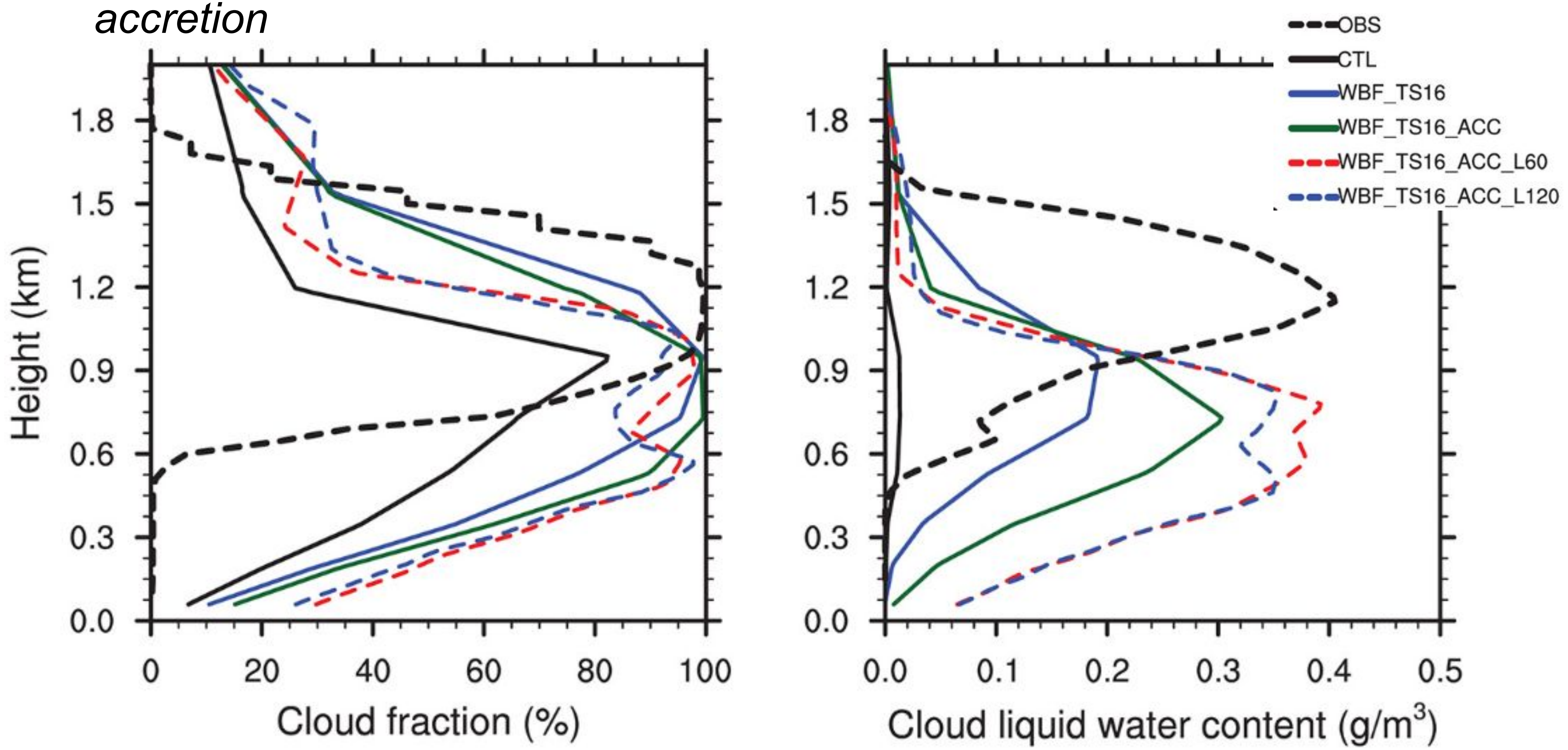
$$q_{i,1\mathrm{M}} \ll q_{i,2\mathrm{M}}$$

$$q_{s,1\mathrm{M}} \gg q_{s,2\mathrm{M}}$$

Sullivan and Voigt (2020) *Comms. Earth*

Issue 3: Certain variables are treated inconsistently across model components.

or for phase heterogeneity between the Bergeron process and accretion



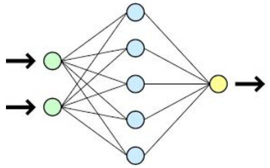
M. Zhang et al. (2019) *J. Geophys. Res.*

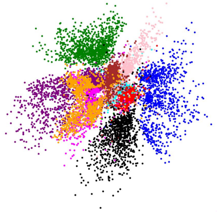
Issue 1: Ice clouds have strong sensitivities to variables for which observations are limited or uncert

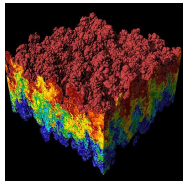
Issue 1b: *But also,* ice clouds have strong sensitivities to the structural formulation of microphysics.

Issue 2: It is unclear how many (and which) degrees of freedom are needed to reliably represent ice microphysical processes.

Issue 2b: It is unclear whether all processes need to be represented under all conditions.







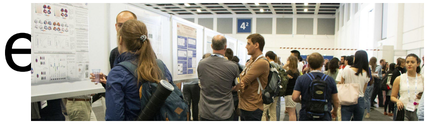
Reduced-Order Modeling for Linearized Representations of Microphysical Process Rates

K. D. Lamb[1], M. van Lier-Walqui[2,3], S. Santos[4], and H. Morrison[5]

Addressing Complexity in Global Aerosol Climate Model Cloud Microphysics

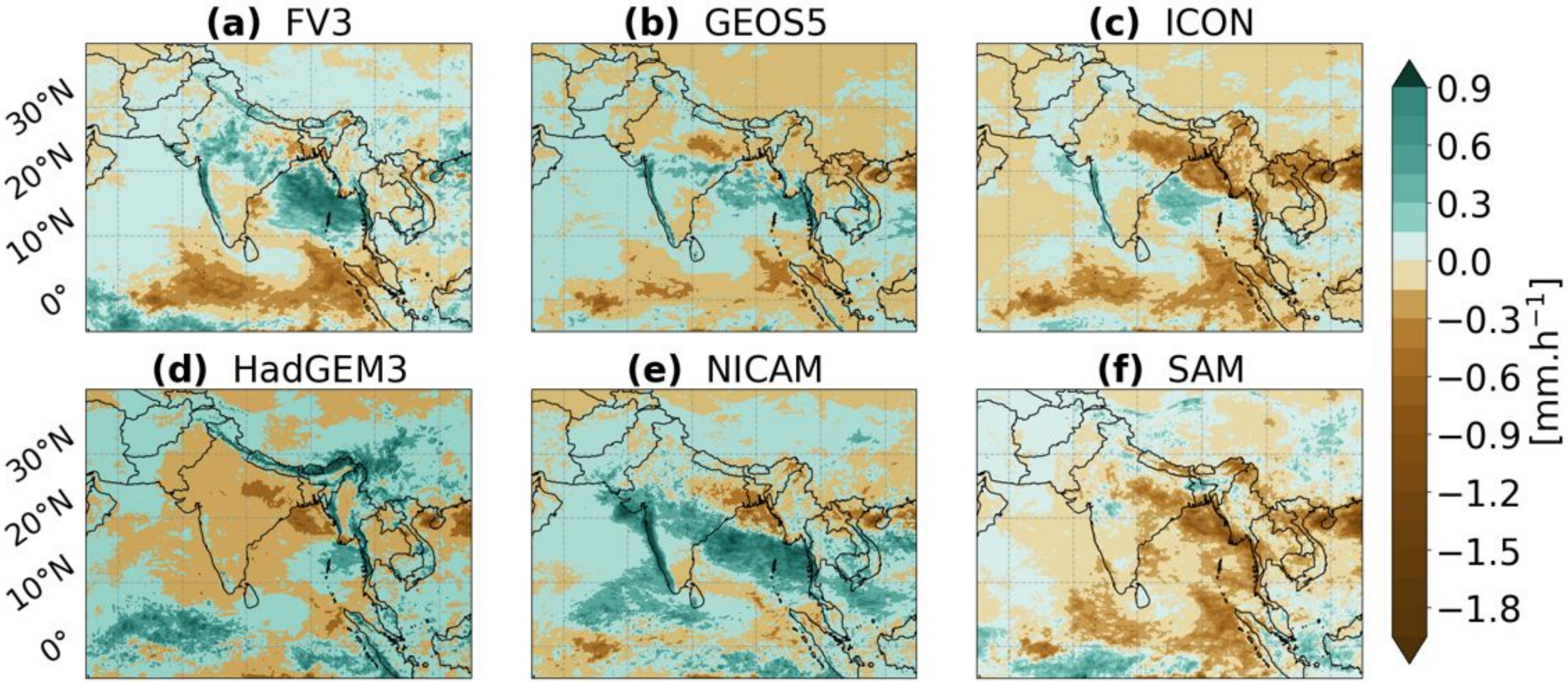
Ulrike Proske[1], Sylvaine Ferrachat[1], Sina Klampt[1,2], Melina Abeling[1,3,4], and Ulrike Lohmann[1]

Issue 3: Certain variables are treated inconsistently across model compone

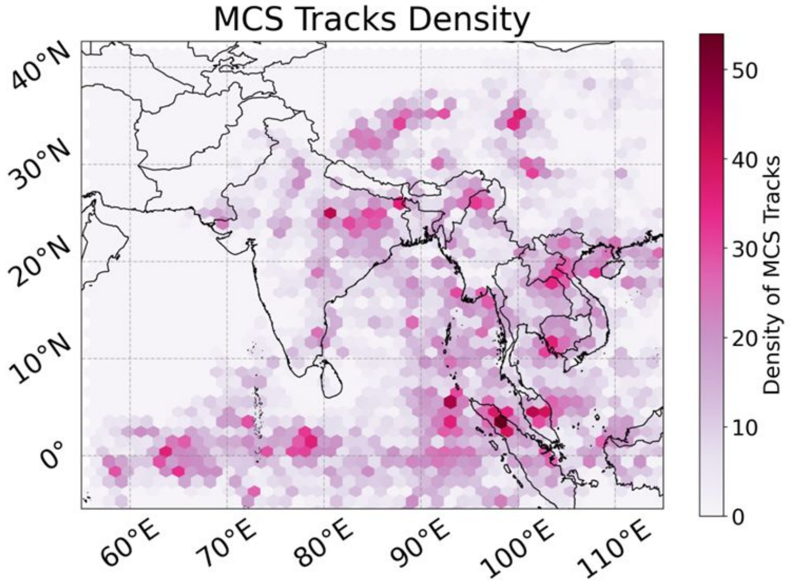


Micro2Macro

Supplemental Slides



Preliminary result: Where MCS track density is highest is also where the SRM precipitation bias is highest.

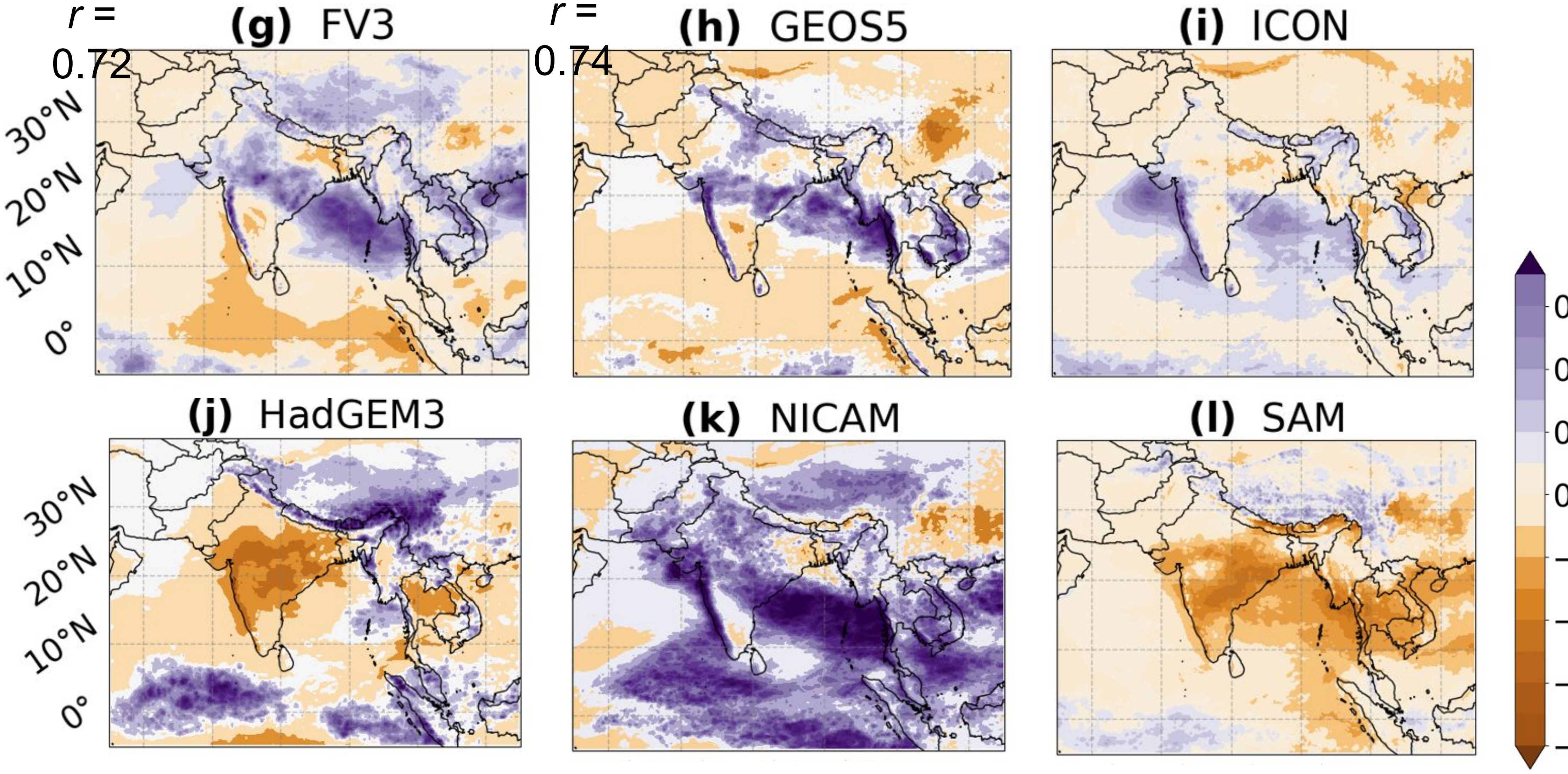


Model resolutions are decreasing…

but benefits of this refinement have a

r = 0.72

r = 0.74



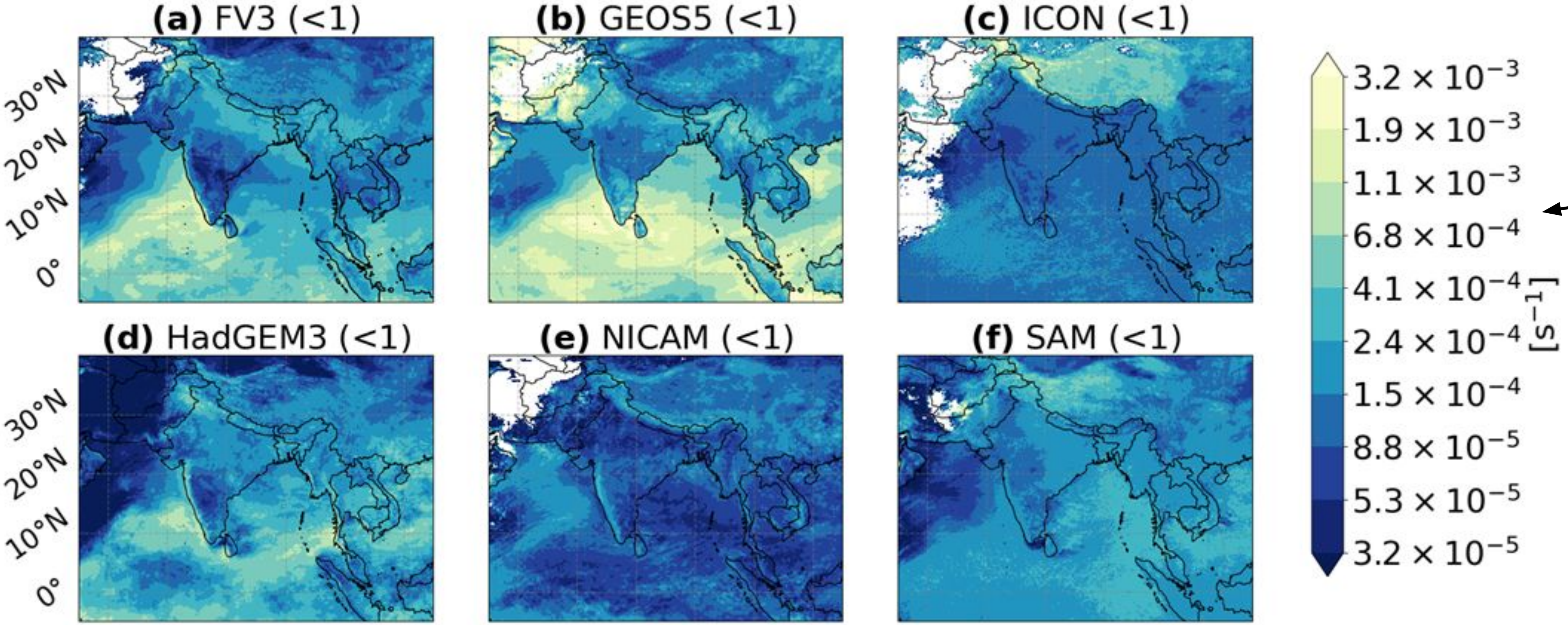
Thabo

Cloud water path bias maps relative to ERA5 reanalysis data, 10 Aug - 10 Sept 2017

Makgoale and Sullivan (2024) *under*

$\dot{P}$ and CWP biases are very different from one model to the next.

→ Very different conversion rates of condensate to $\dot{P}$



Inverse atmospheric residence times

$$\epsilon = \frac{<\dot{P}>}{<\mathrm{CWP}>} \qquad \frac{[\mathrm{kg\ m^{-2}\ s^{-1}}]}{[\mathrm{kg\ m^{-2}}]}$$

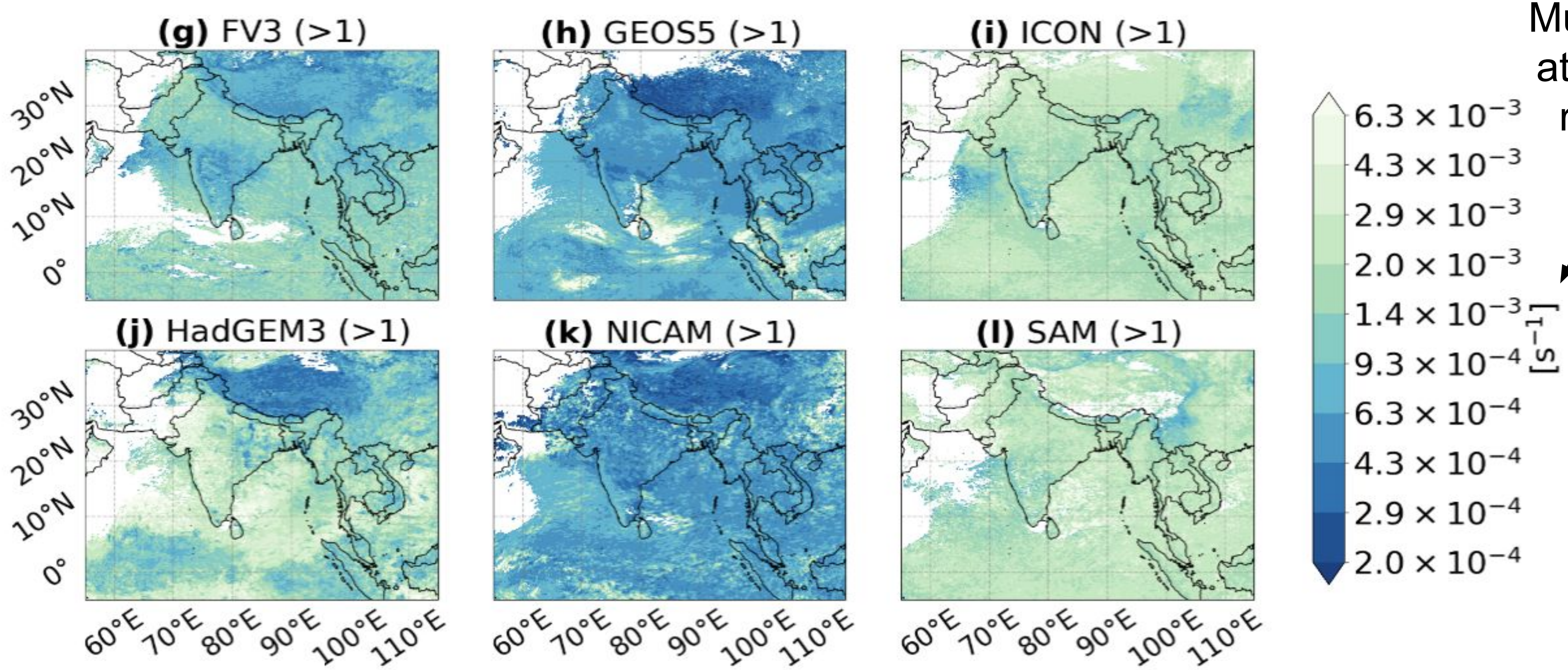
rainfall events $\dot{P} < 1$ mm h^{-1}

Makgoale and Sullivan (2024) *under*

Li et al. 2022 *Nat.*

$\dot{P}$ and CWP biases are very different from one model to the next.

→ Very different conversion rates of condensate to $\dot{P}$



Much shorter atmospheric residence times

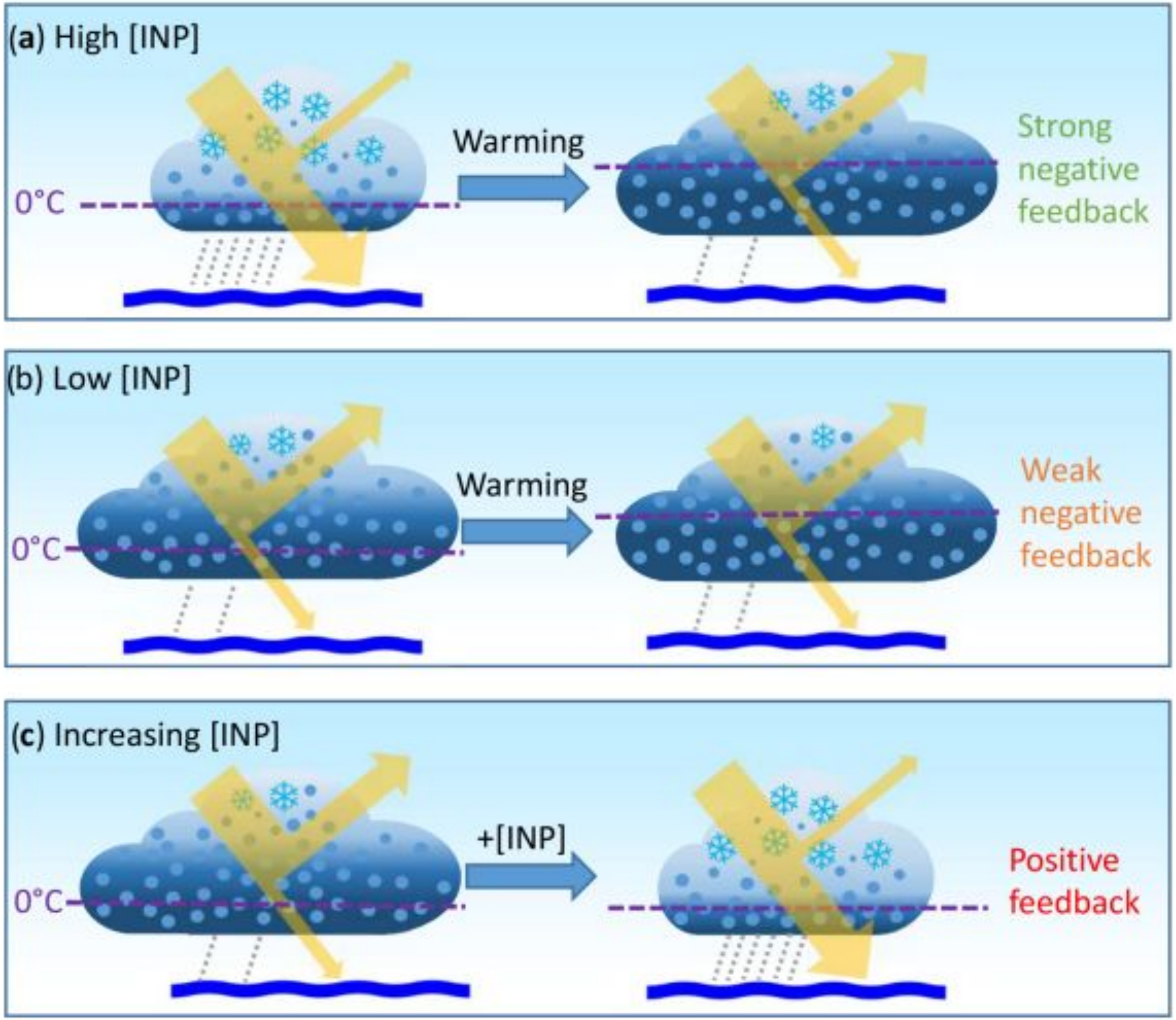
$$\epsilon = \frac{<\dot{P}>}{<\mathrm{CWP}>}$$

events $\dot{P} > 1$ mm h^{-1}

Much more *intermodel* variability than *intramodel* variability in ϵ for intense events

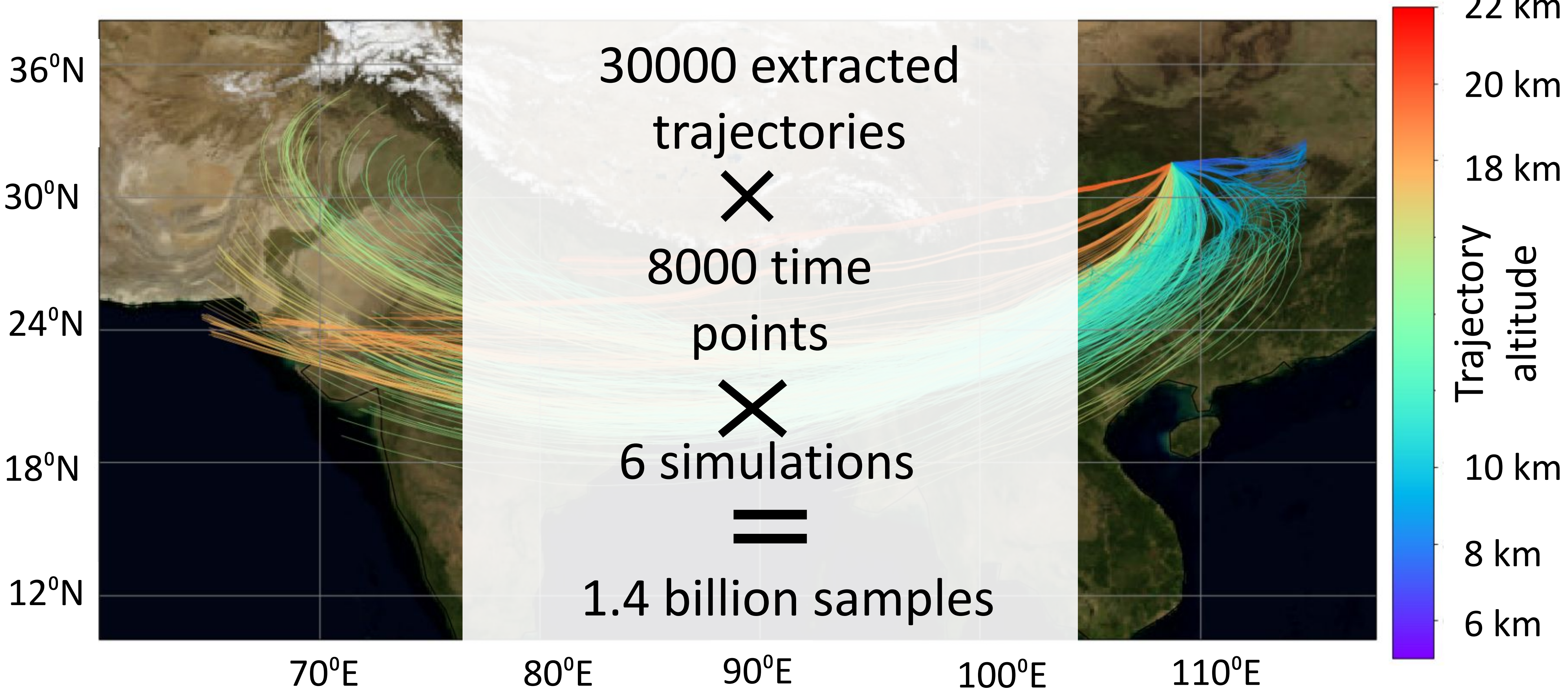
Makgoale and Sullivan (2024) *under*

Li et al. 2022 *Nat.*



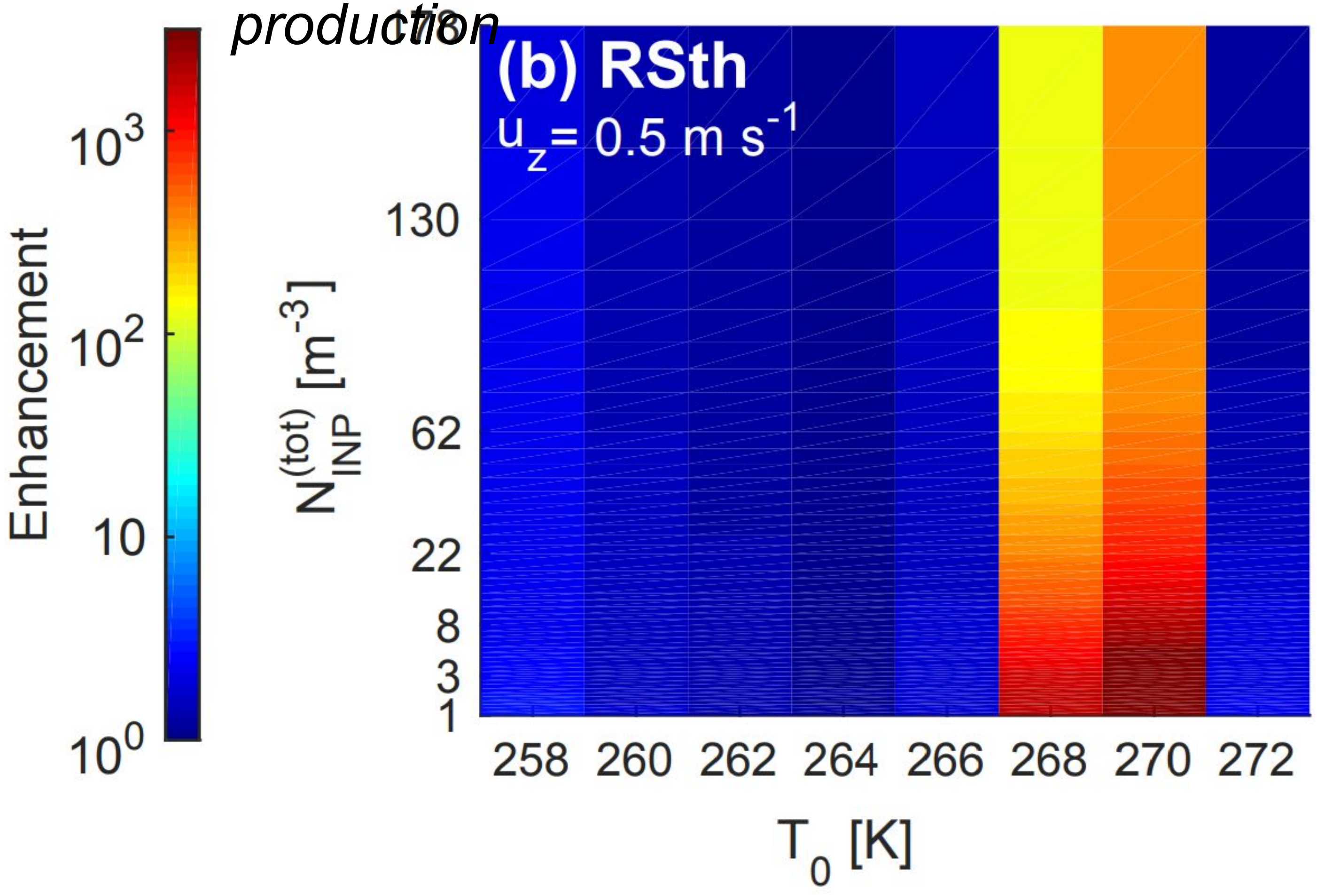
Murray et al. (2021) *Atmos. Chem. Phys.*

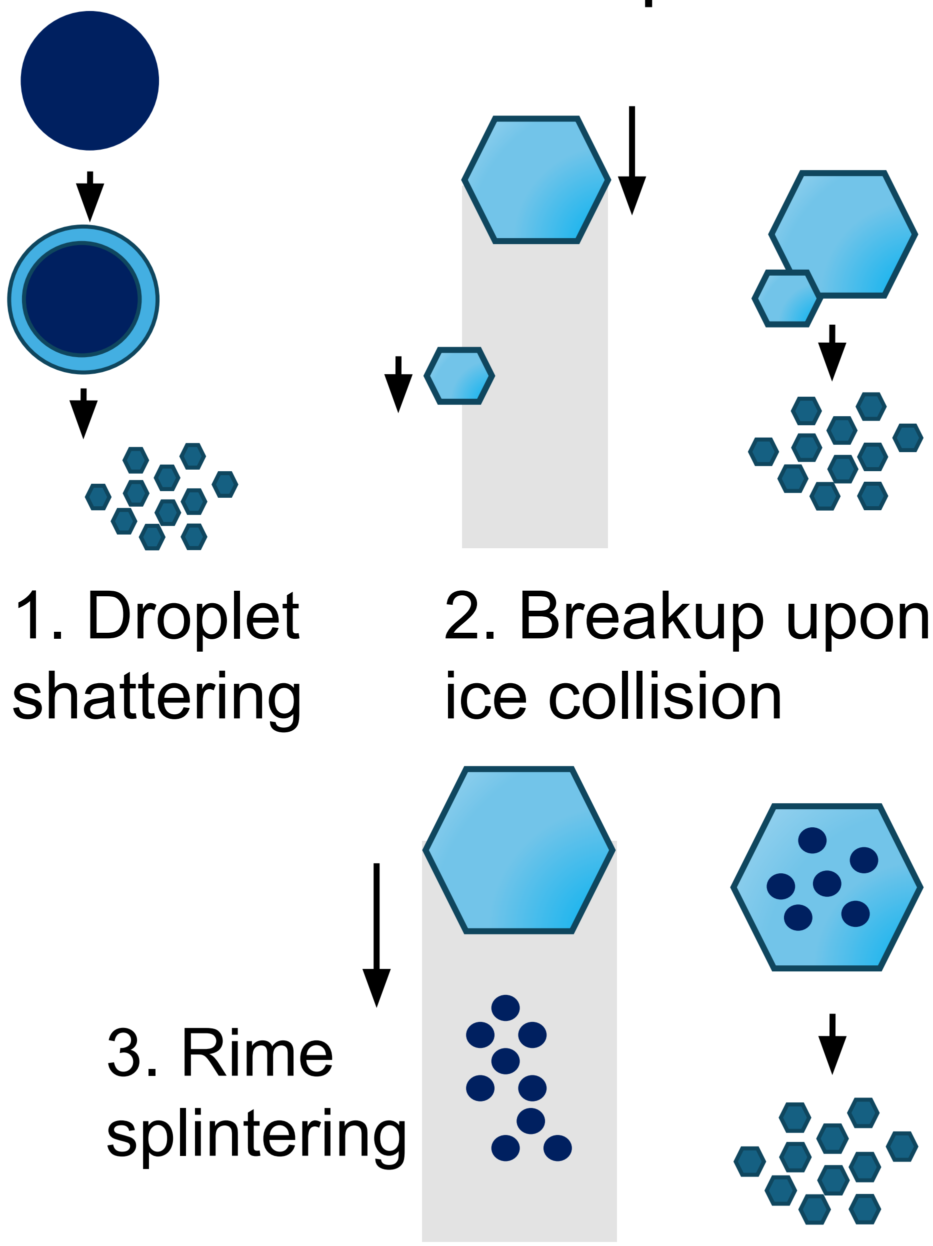
Feedbacks are constrained with fixed inputs along trajectories.



Issue 2b: It is unclear whether all processes need to be represented under all conditions.

such as secondary ice production





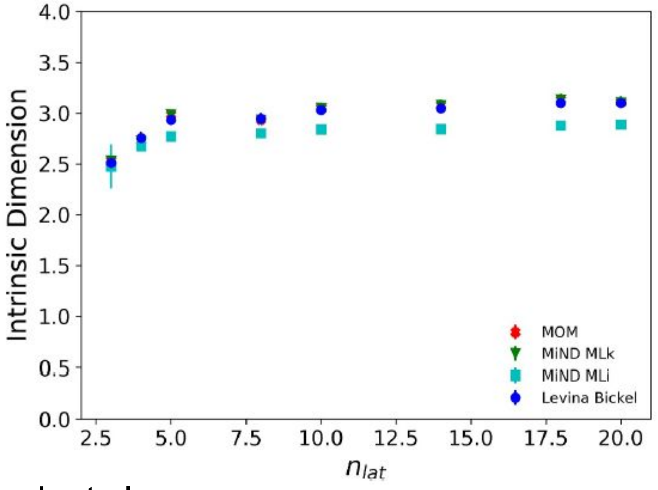
Sullivan et al. (2018) *Atmos. Chem. Phys.*

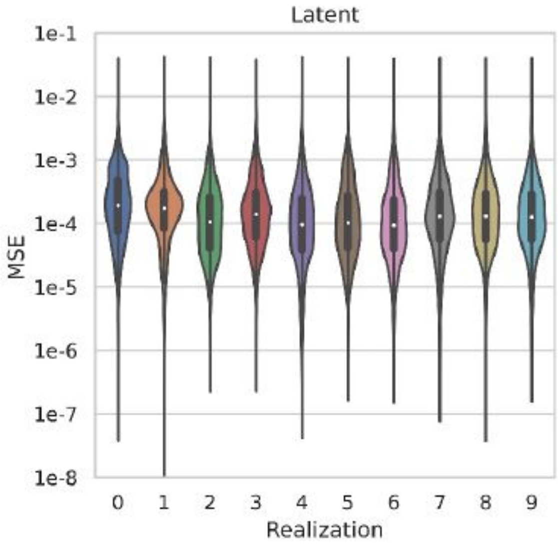
Other studies with similar findings: Korolev and Leisner (2020) *Atmos. Chem. Phys.*, Waman et al. (2022) *J. Atm. Sci.*, Pasquier et al. (2022) *Atmos. Chem. Phys.*

Issue 2

Perhaps reduced-order modeling or machine learning / emulators provide solutions here?

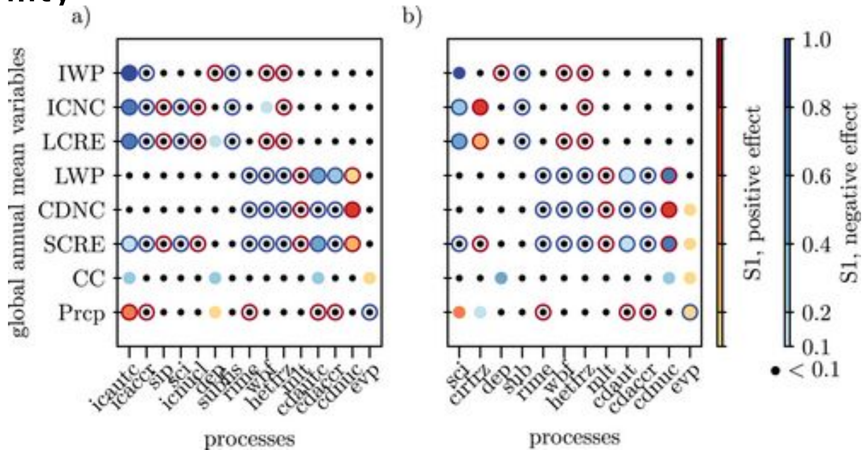
Example 1: Identification of an ‘intrinsic dimension’ for collisic





Lamb et al. 2024

Example 2: An emulated perturbed parameter ensemble shows that autoconversion formulations dominate a lot of ice-phase variability



Proske et al. 2023